ARSET
Applied Remote Sensing Training
http://arset.gsfc.nasa.gov
@NASAARSET

Current and Future Satellite Capabilities for Air Quality Monitoring: An Overview

**Pawan Gupta, Melanie Follette-Cook**

Monday, November 14, 2016
2nd International Smoke Symposium
Long Beach, CA, USA

Objectives

- Learn about existing satellite capabilities for air quality monitoring around the world

- Learn about upcoming and future satellite missions for air quality monitoring

- Learn fundamentals of satellite remote sensing
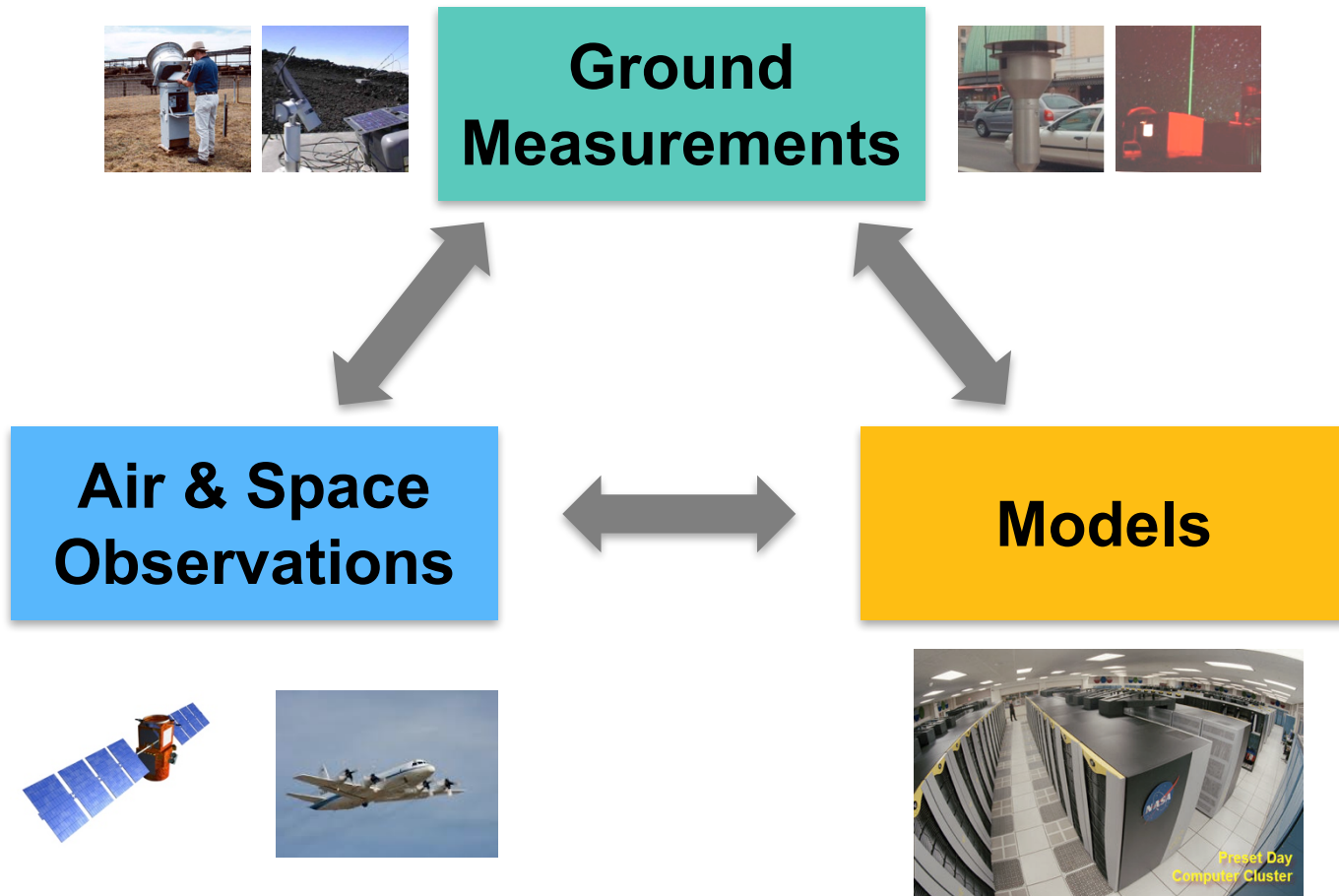
Motivation – Tiny but Potent

Effects of Atmospheric Aerosols
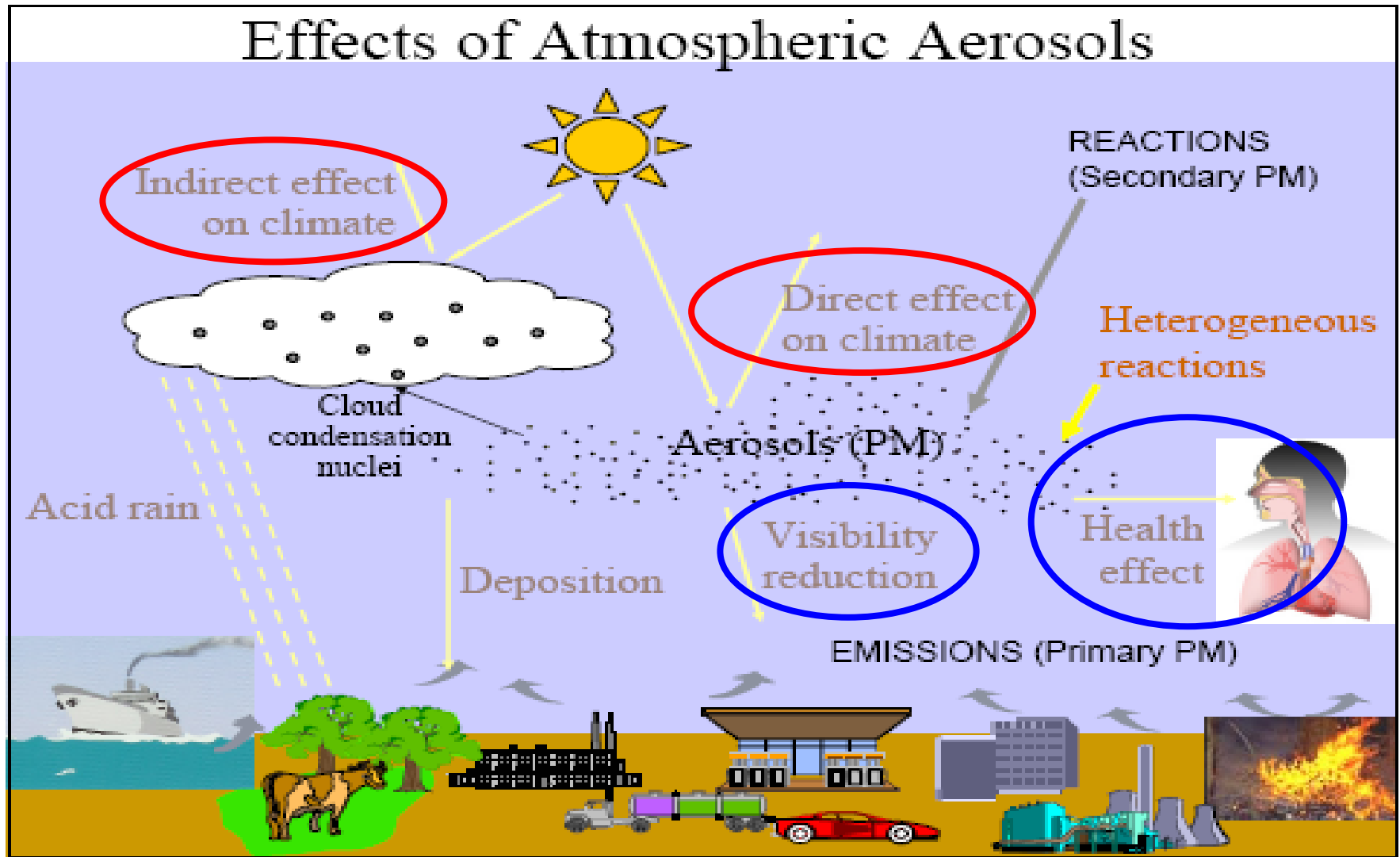
Pollution Sources

- Atmospheric aerosols are highly variable in space and time
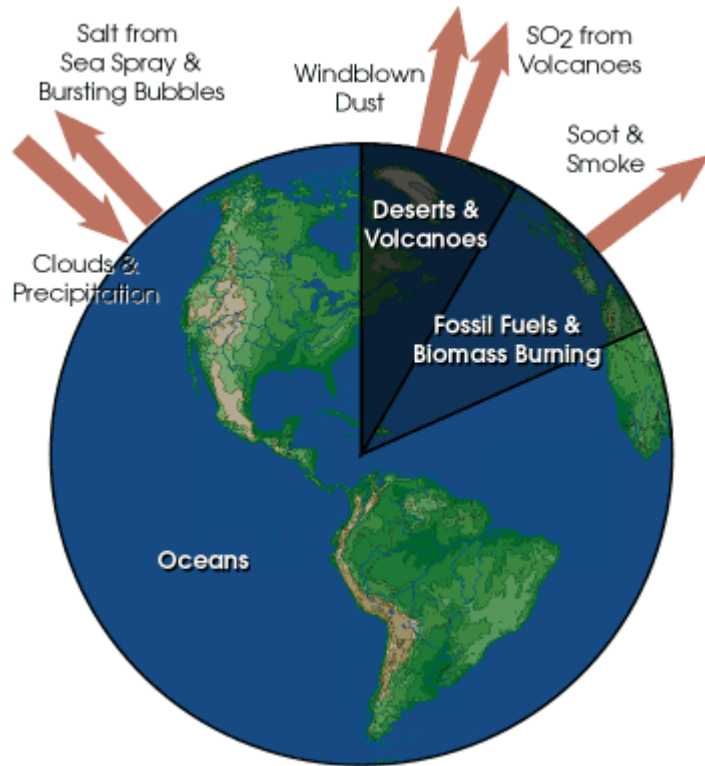
Air Pollution Monitoring

Ground Measurements

Air & Space Observations

Models

Preset Day Computer Cluster

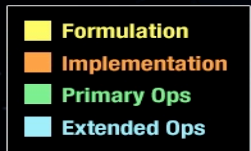**Why use satellite data?**

Global Status of PM2.5 Monitoring

- Many countries do not have PM2.5 mass measurements

- Spatial distribution of air pollution from existing ground network does not support high population density

- 2,400 out of 3,100 counties in the U.S. (31% of the total population) have no PM monitoring in the county

- Surface measurements are not cost effective

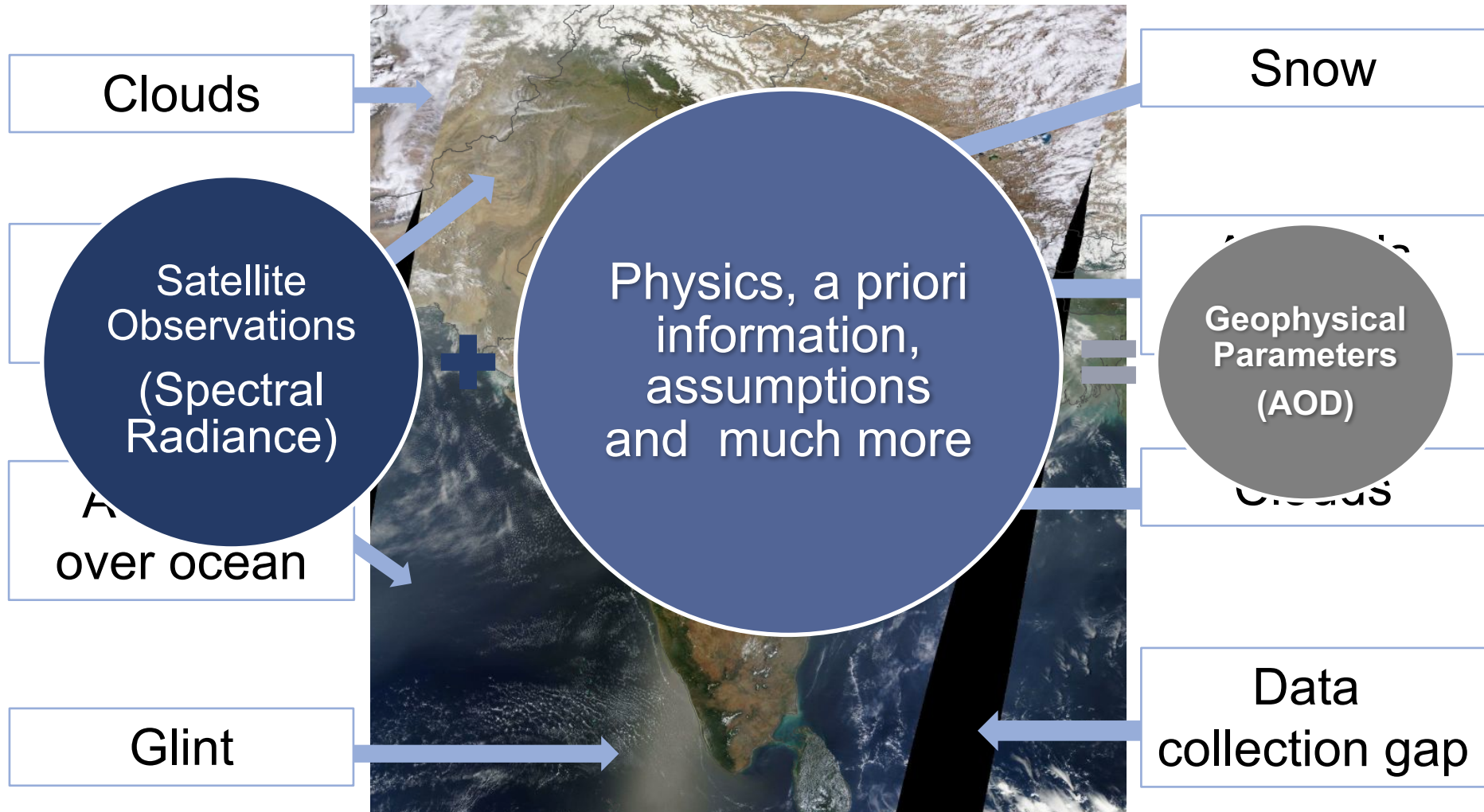- How about using remote sensing satellite?
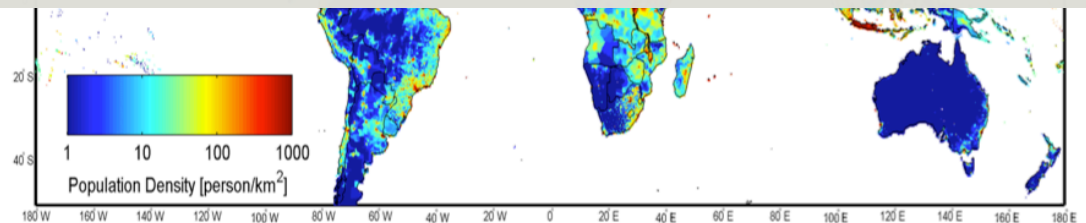
NASA Earth Science
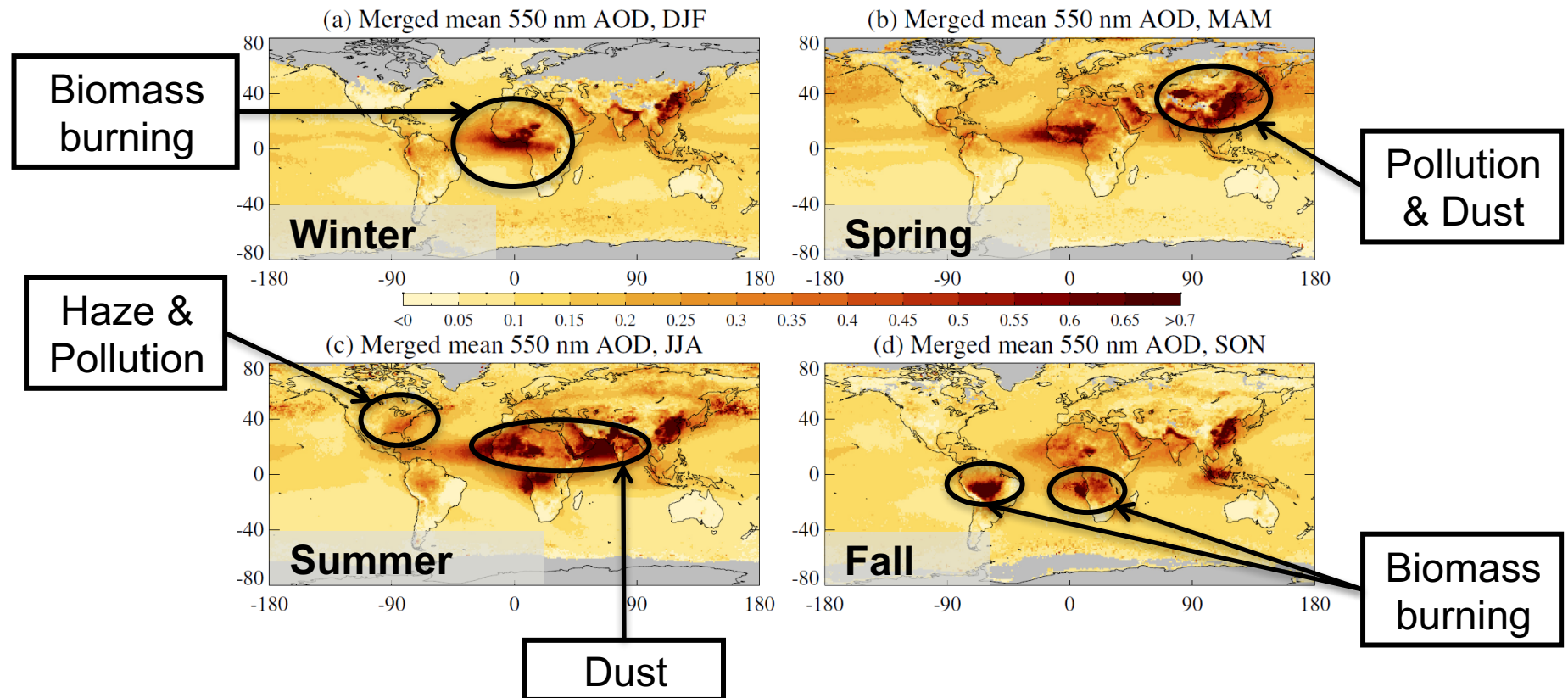
Current and Upcoming Missions

What can we learn from true color imagery?

MODIS Terra Image, April 19, 2013

Clouds

Snow

Satellite Observations (Spectral Radiance)

+

Physics, a priori information, assumptions and much more

=

Geophysical Parameters (AOD)

A... over ocean

Clouds
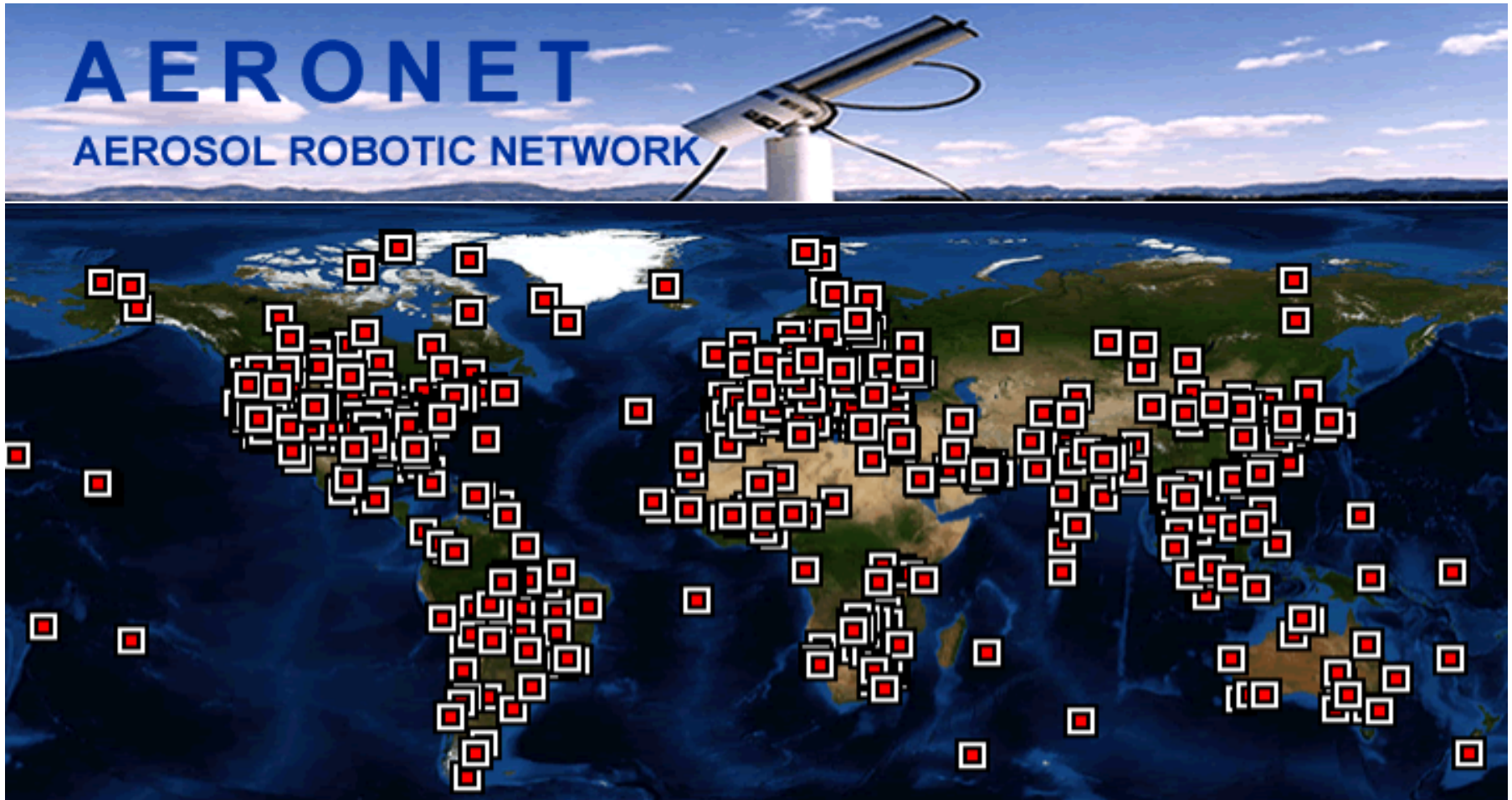
Glint

Data collection gap

Aerosols from Satellites

Aerosol Optical Thickness (MODIS Aqua)

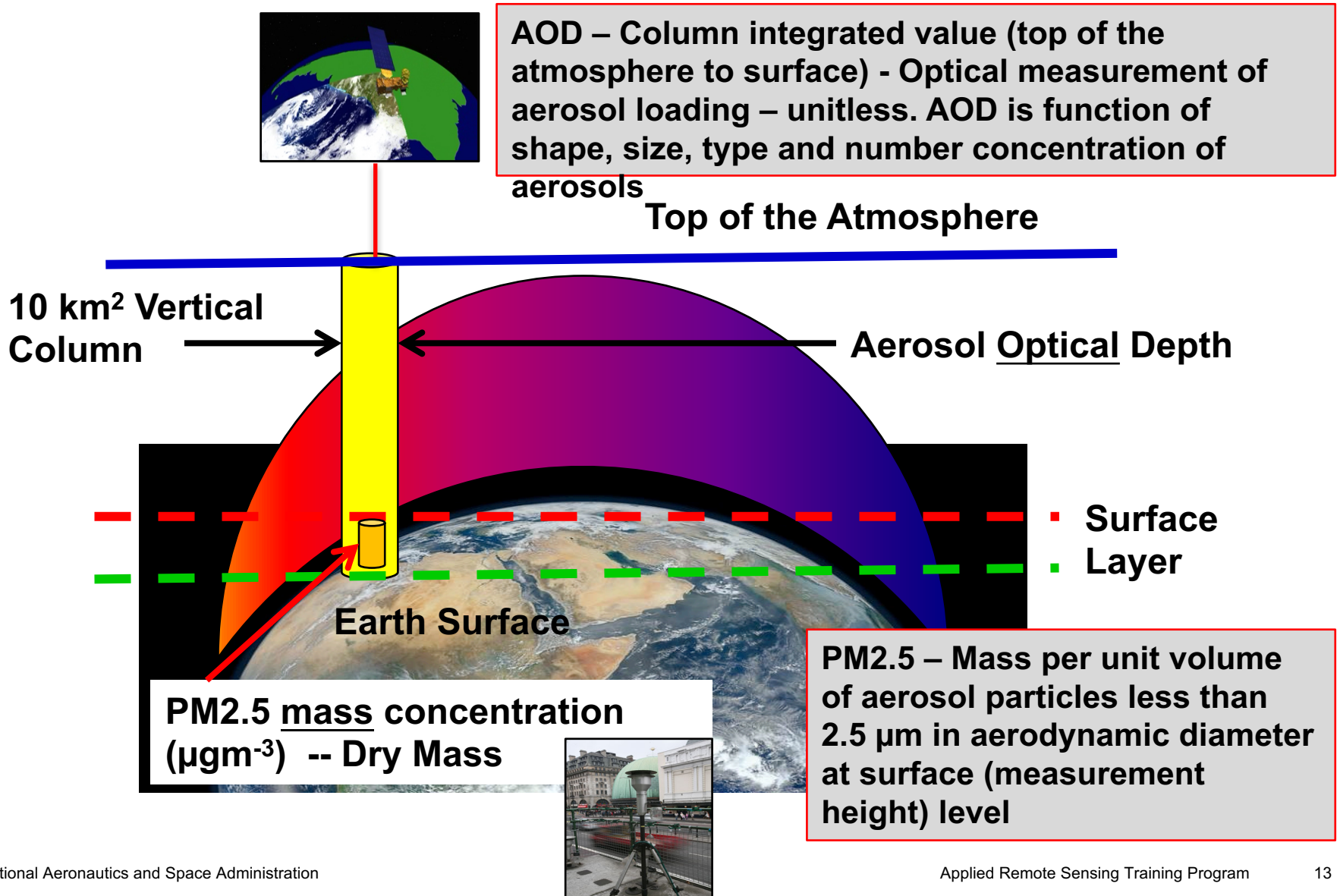**Several satellites provide state-of-the-art aerosol measurements globally, on a daily basis**

AERONET

http://aeronet.gsfc.nasa.gov/

AERONET measurements of Aerosol Optical Depth are considered ground truth and used to validate satellite aerosol retrievals

Applications
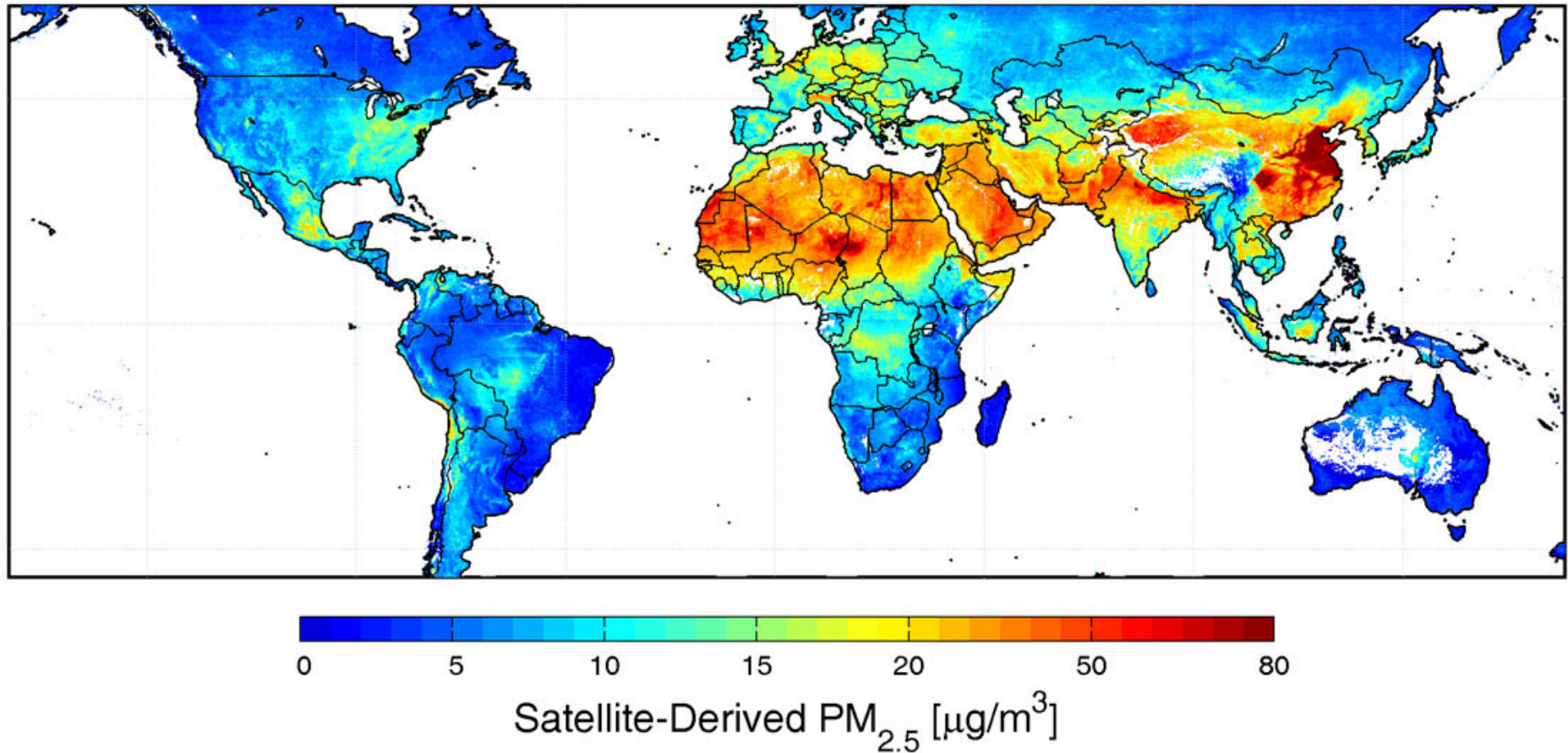
Satellite vs. Ground Observation

AOD – Column integrated value (top of the atmosphere to surface) - Optical measurement of aerosol loading – unitless. AOD is function of shape, size, type and number concentration of aerosols

Top of the Atmosphere

10 km² Vertical Column

Aerosol Optical Depth

Surface Layer

Earth Surface

PM2.5 mass concentration (μgm^{-3}) -- Dry Mass

PM2.5 – Mass per unit volume of aerosol particles less than 2.5 μm in aerodynamic diameter at surface (measurement height) level
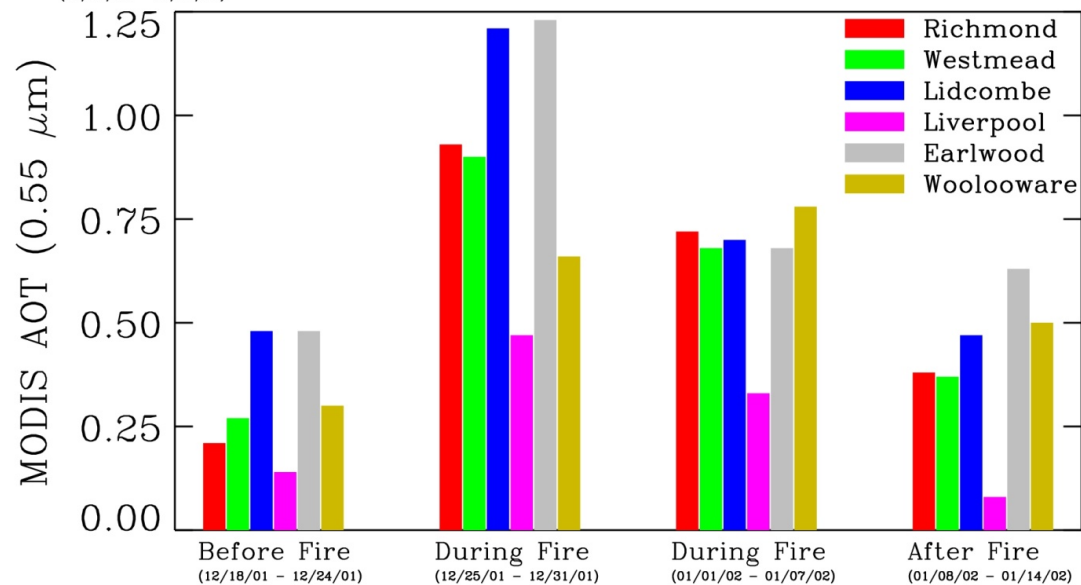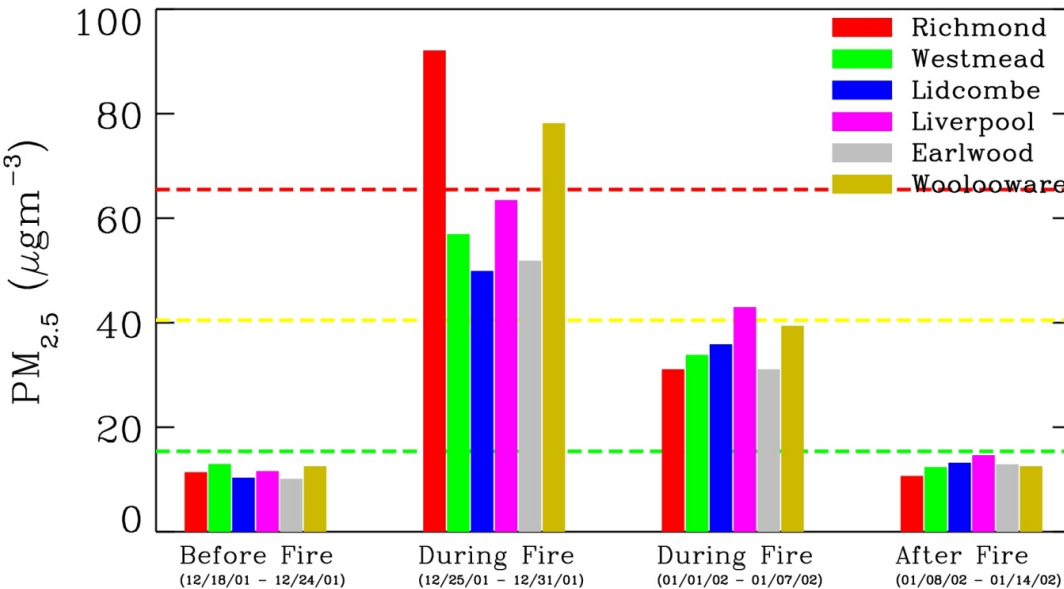
Annual Mean PM2.5 from Satellite Observations

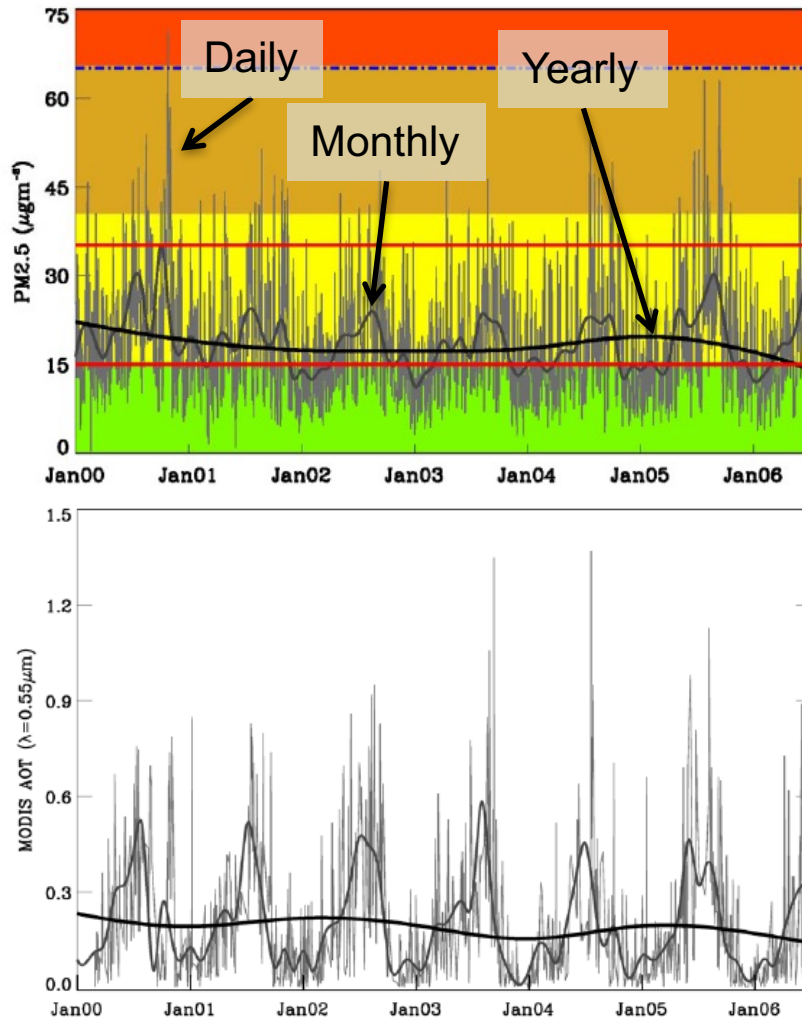Source: van Donkelaar et al., 2006, 2009

Application of Satellite Observations: Bushfires in Sydney, Australia

Credit: Gupta and Christopher, 2007
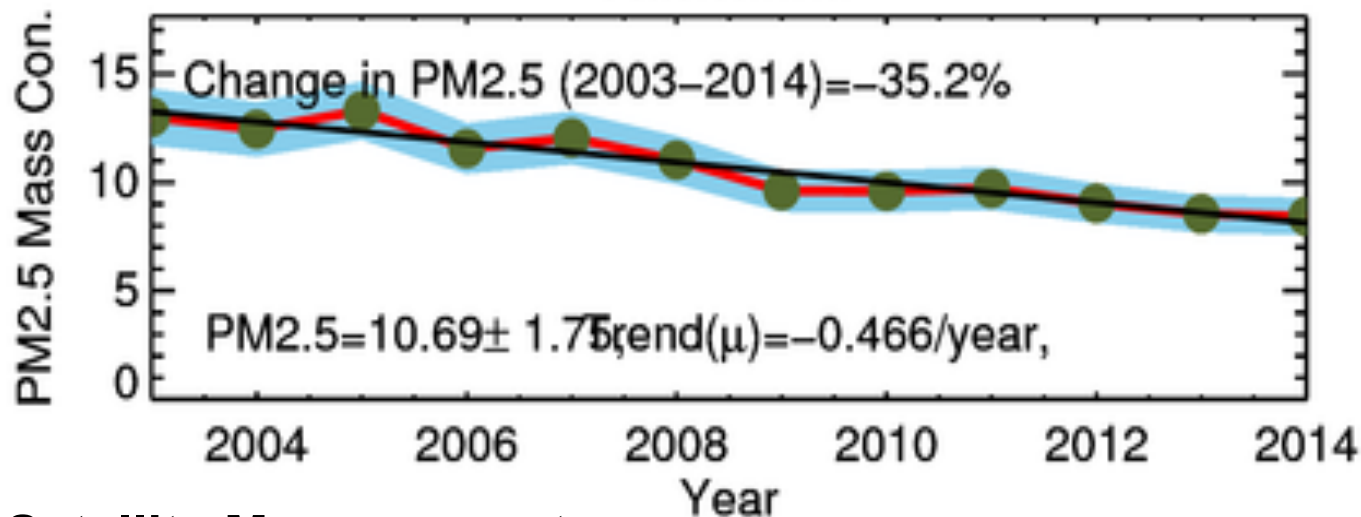
Air Quality Trends

Birmingham, AL

A decreasing trend in annual PM2.5 was noted with the almost 22% reduction in PM2.5 mass concentration observed in 2006 compared to 2002

MODIS-Terra Collection 5, Level 2, 10km^2 AOTs for 2000-2006
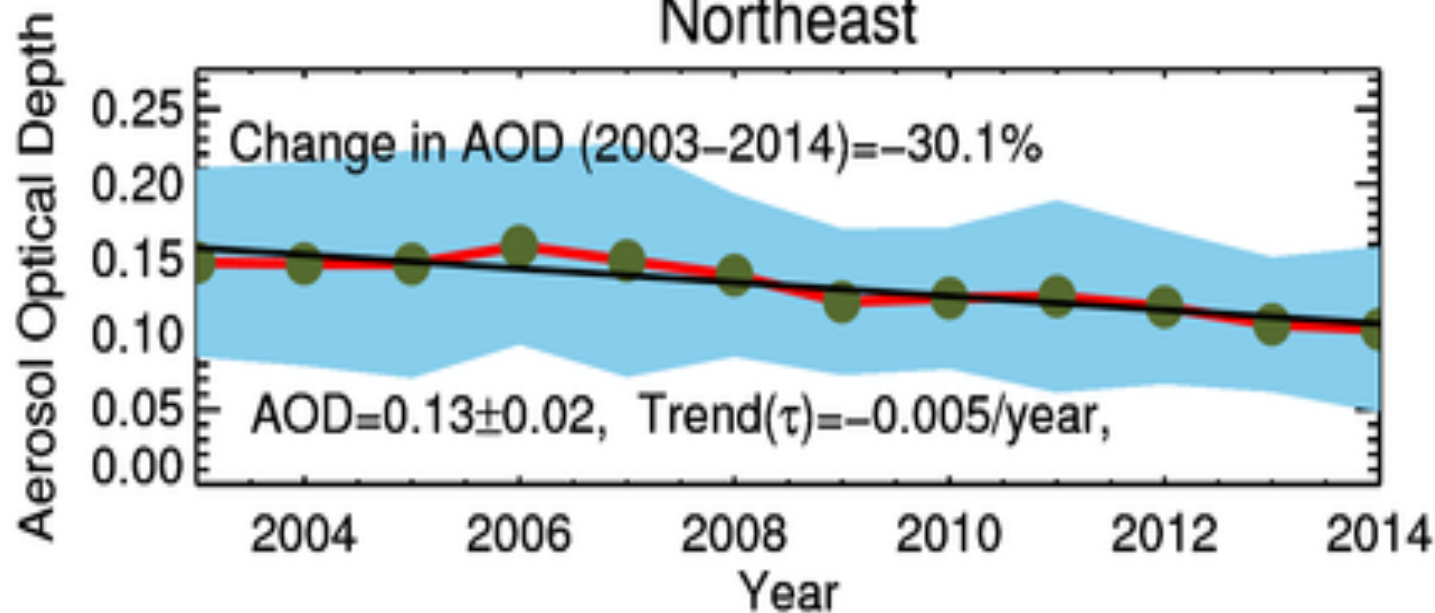
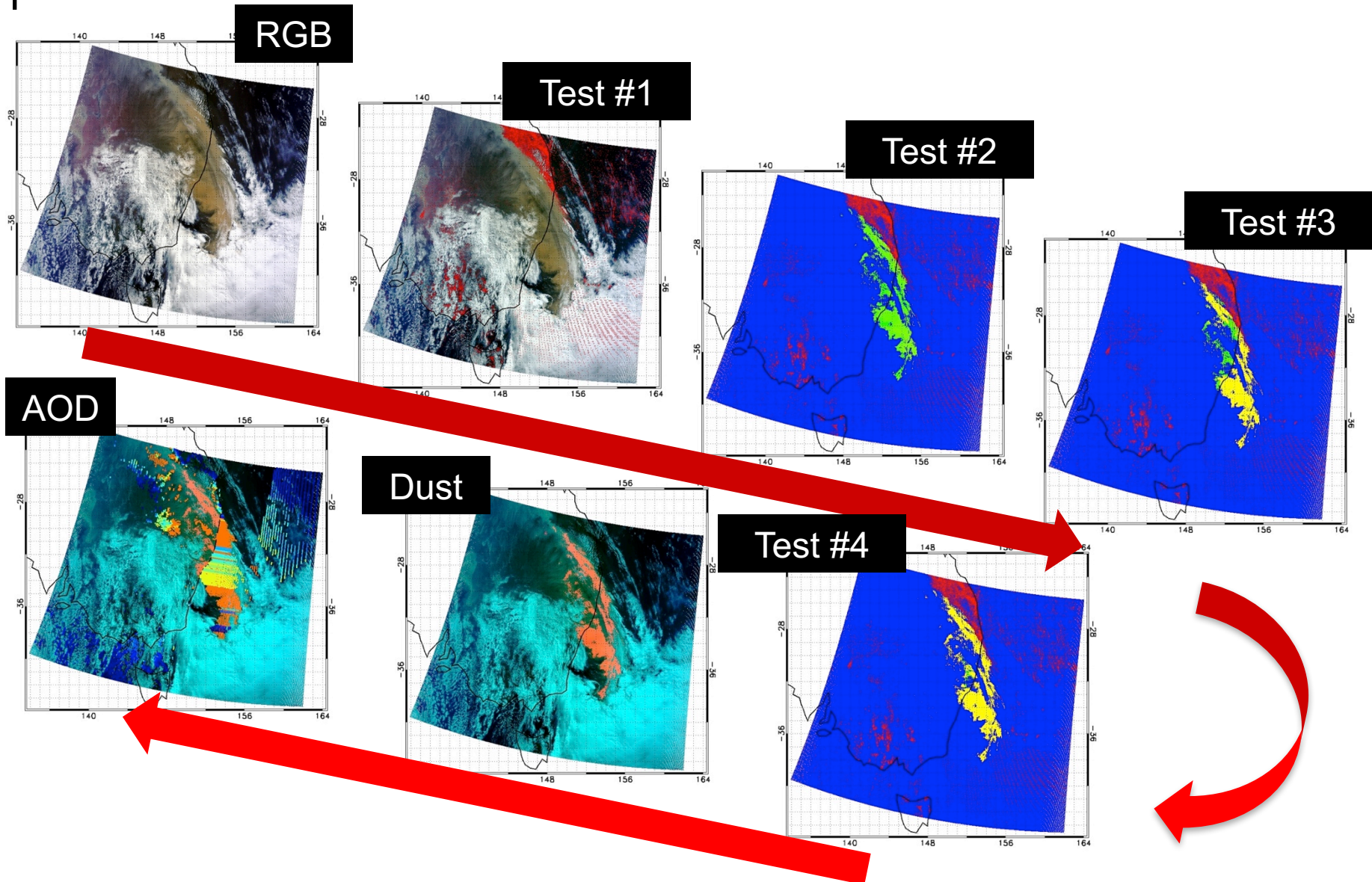Source: Gupta and Christopher, 2007

Surface Measurement

Northeast

Change in PM2.5 (2003–2014)=−35.2%

$PM2.5 = 10.69 \pm 1.75$, $Trend(\mu) = -0.466/year$,

Satellite Measurement

Northeast

Change in AOD (2003–2014)=−30.1%

$AOD = 0.13 \pm 0.02$, $Trend(\tau) = -0.005/year$,
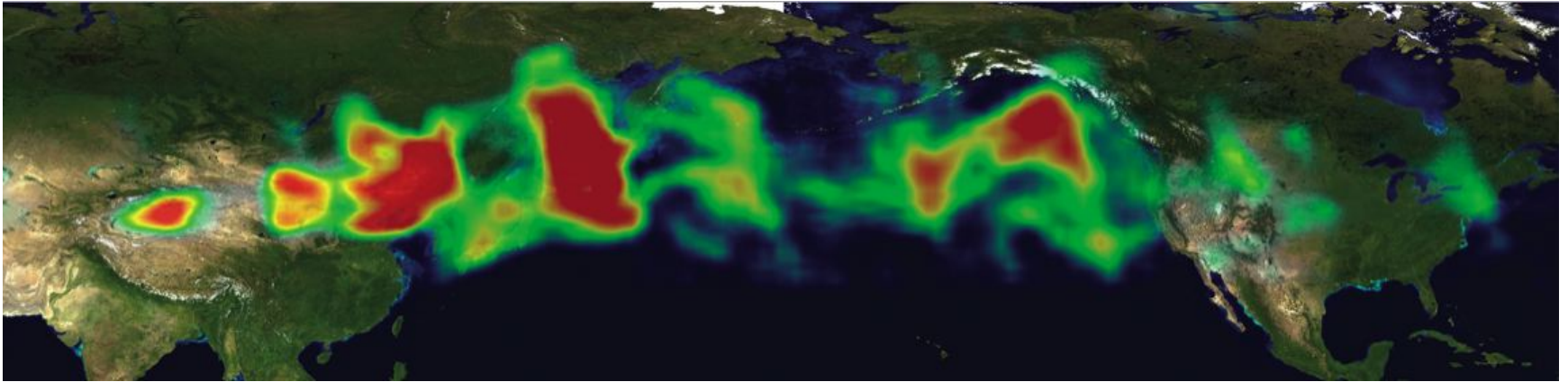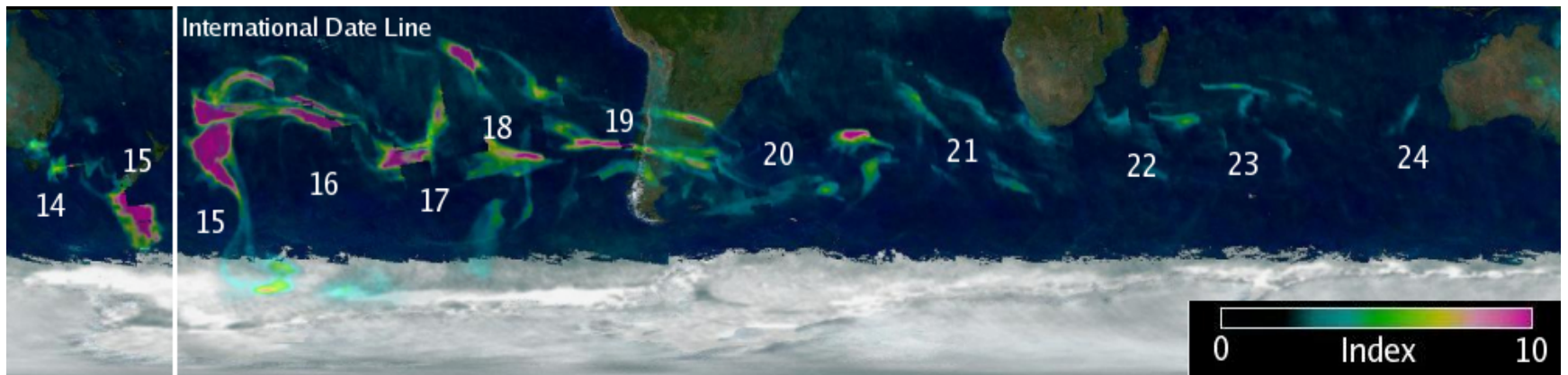
Dust & Smoke Monitoring

Long Range Transport
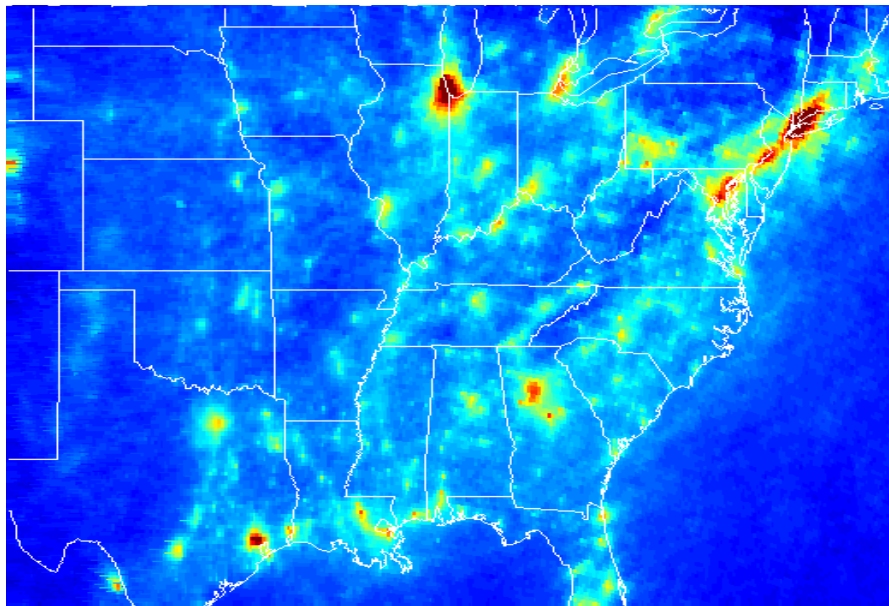
Dust from Mongolian Deserts Reaches the U.S.

Smoke Travels Around the World in 11 Days
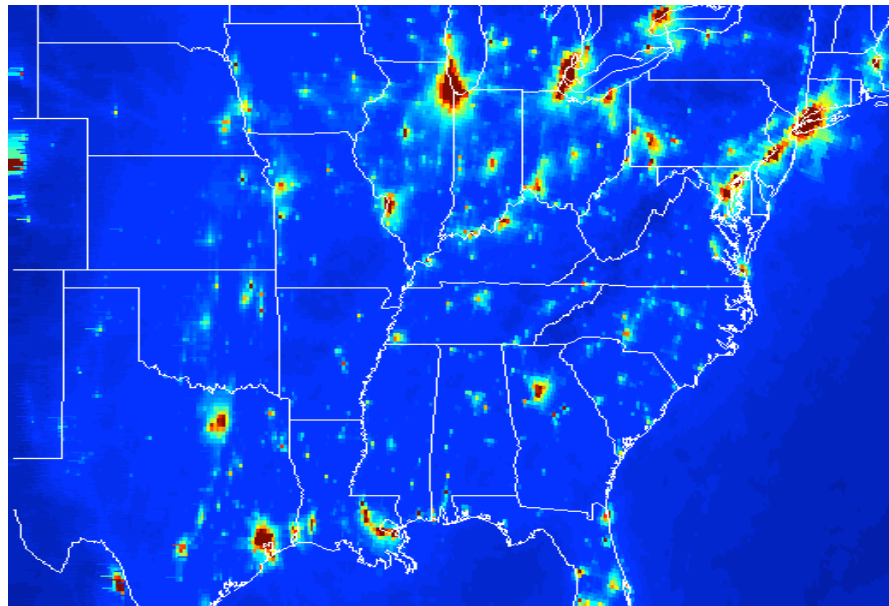
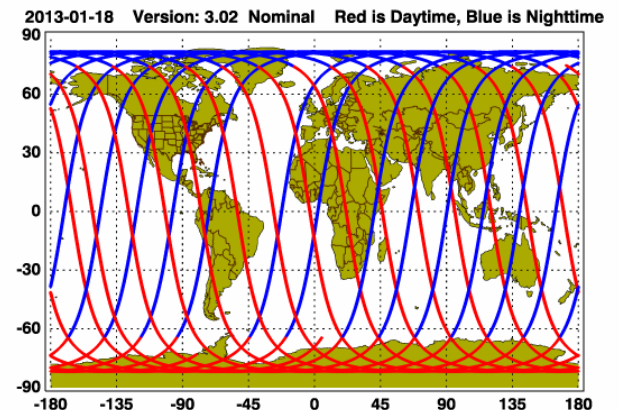# Model-Satellite Inter-Comparison
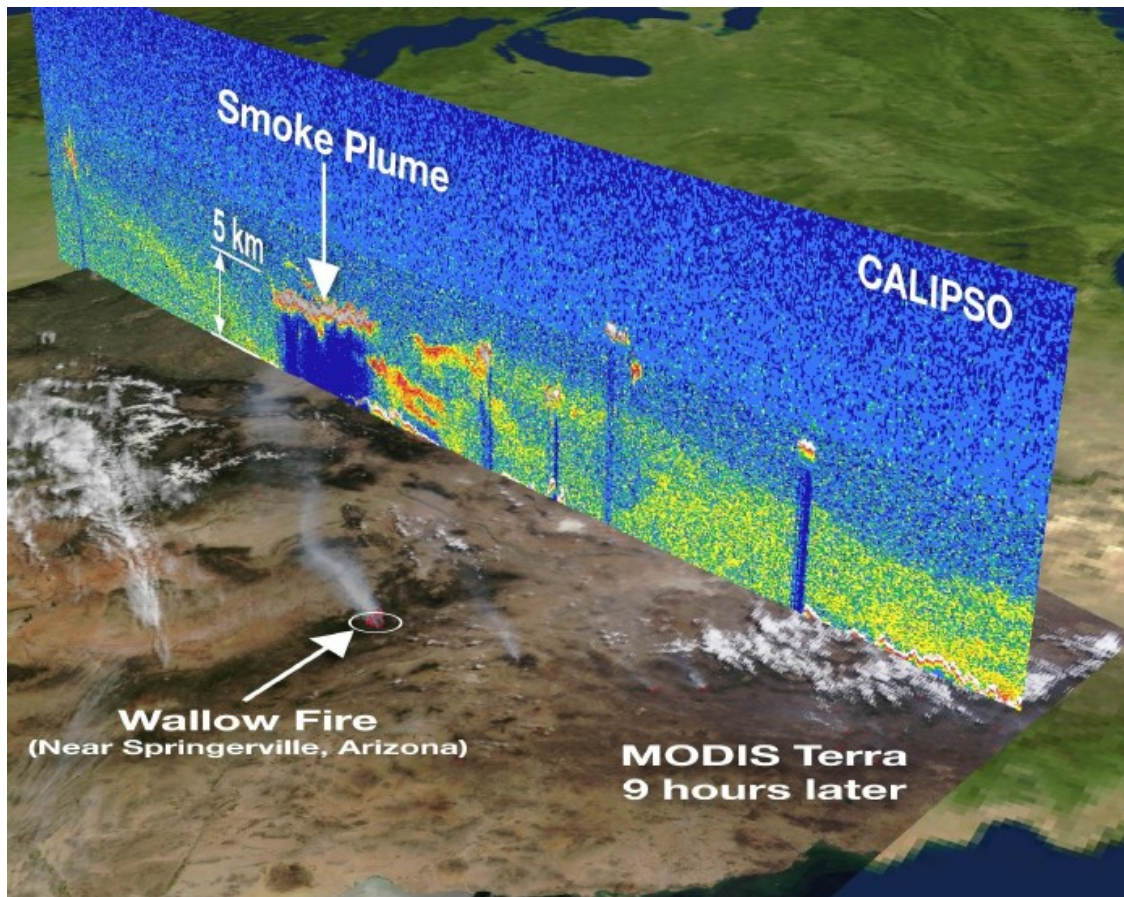
CMAQ Model NO$_2$

OMI NO$_2$

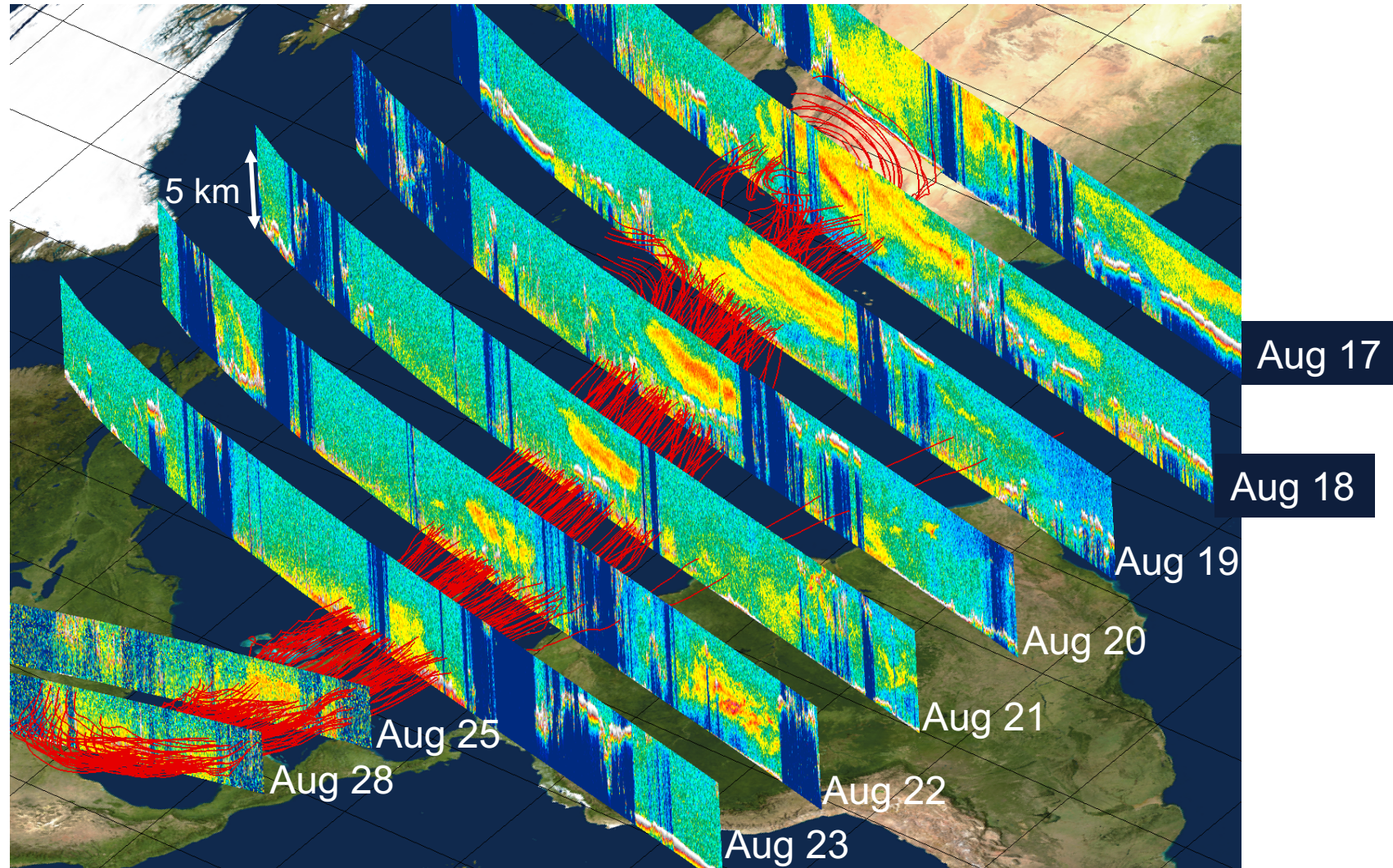# Vertical Profiles of Aerosols

CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
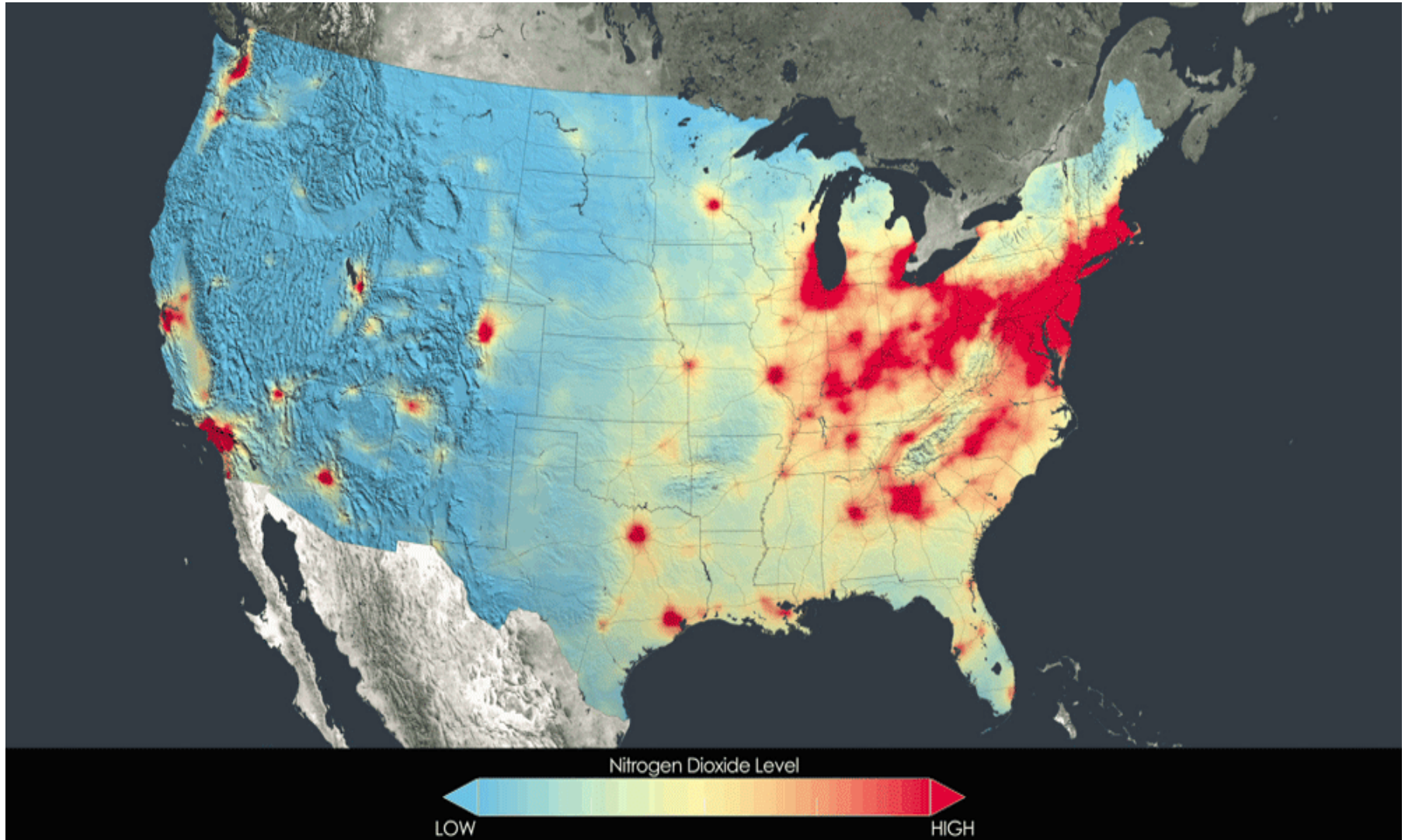

CALIPSO Browse Images
http://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/

Example of CALIPSO Data

Major Saharan Dust Transport Event: Aug 17-28

5 km

Aug 17
Aug 18
Aug 19
Aug 20
Aug 21
Aug 22
Aug 23
Aug 25
Aug 28

Courtesy of: Dave Winker, P.I. CALIPSO

NO$_2$ Trends Over the United States

Nitrogen Dioxide Level

LOW — HIGH

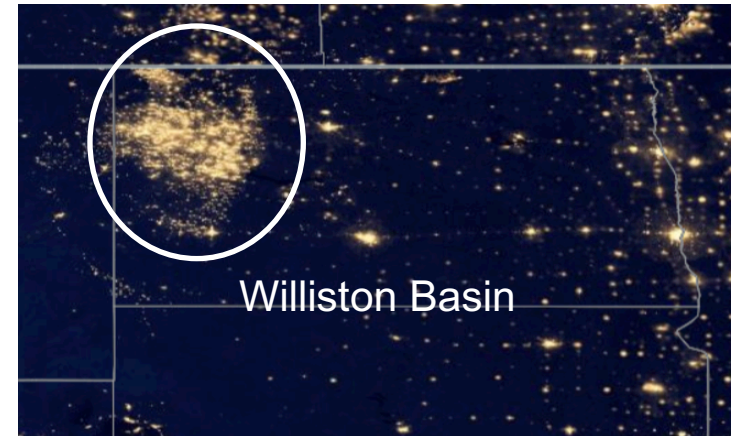# OMI Detects NO₂ Increases from ONG Activities

2005-2014
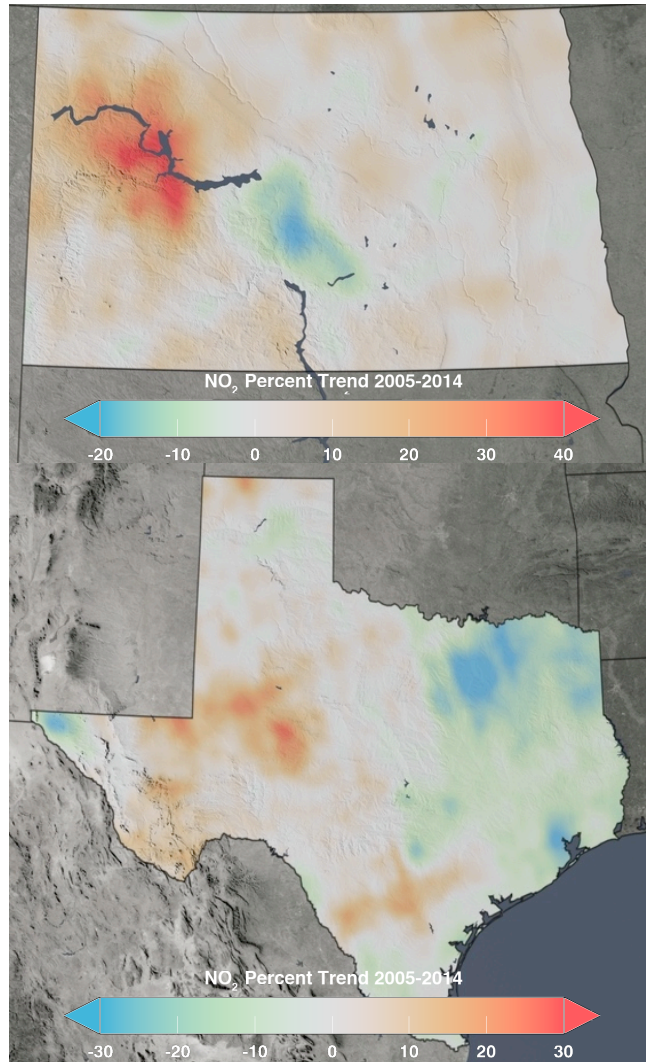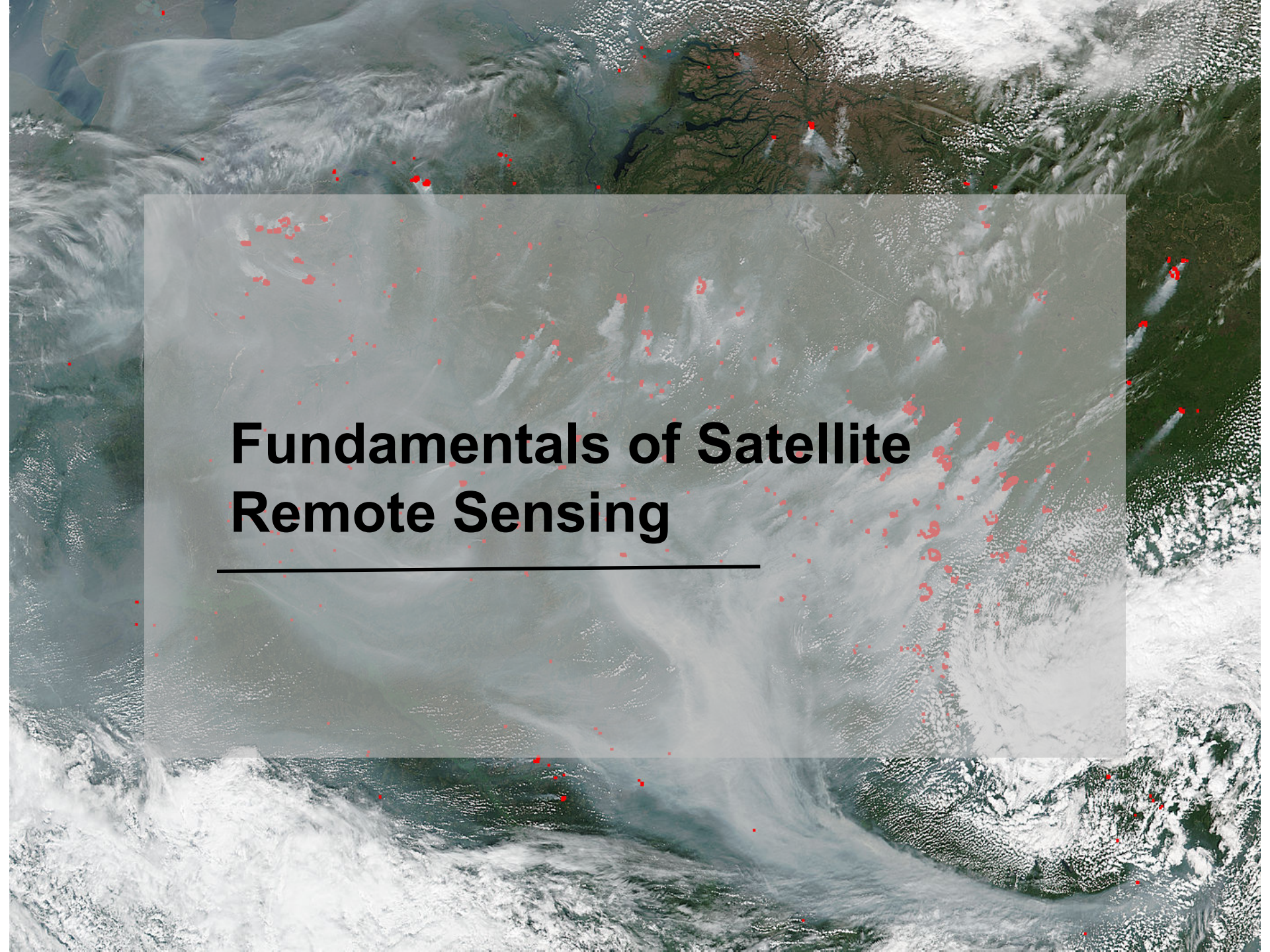
Suomi NPP VIIRS Lights at Night
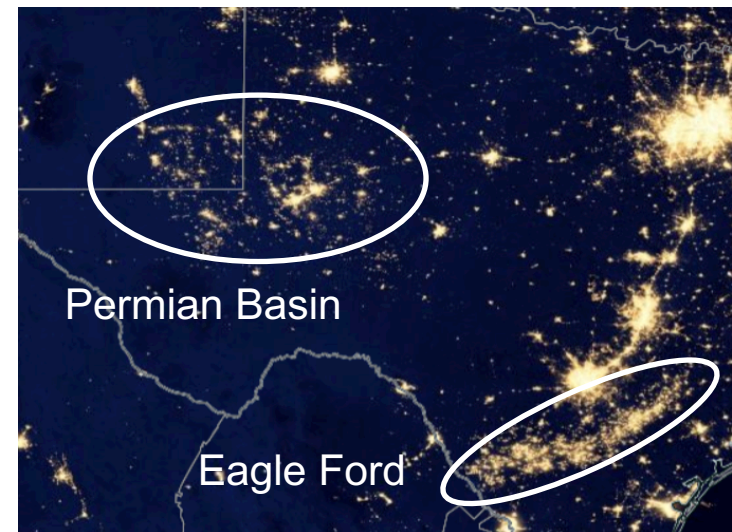
North Dakota

NO₂ Percent Trend 2005-2014
-20 -10 0 10 20 30 40

Williston Basin

Texas

NO₂ Percent Trend 2005-2014
-30 -20 -10 0 10 20 30

Permian Basin

Eagle Ford

Fundamentals of Satellite Remote Sensing

What do satellites measure?
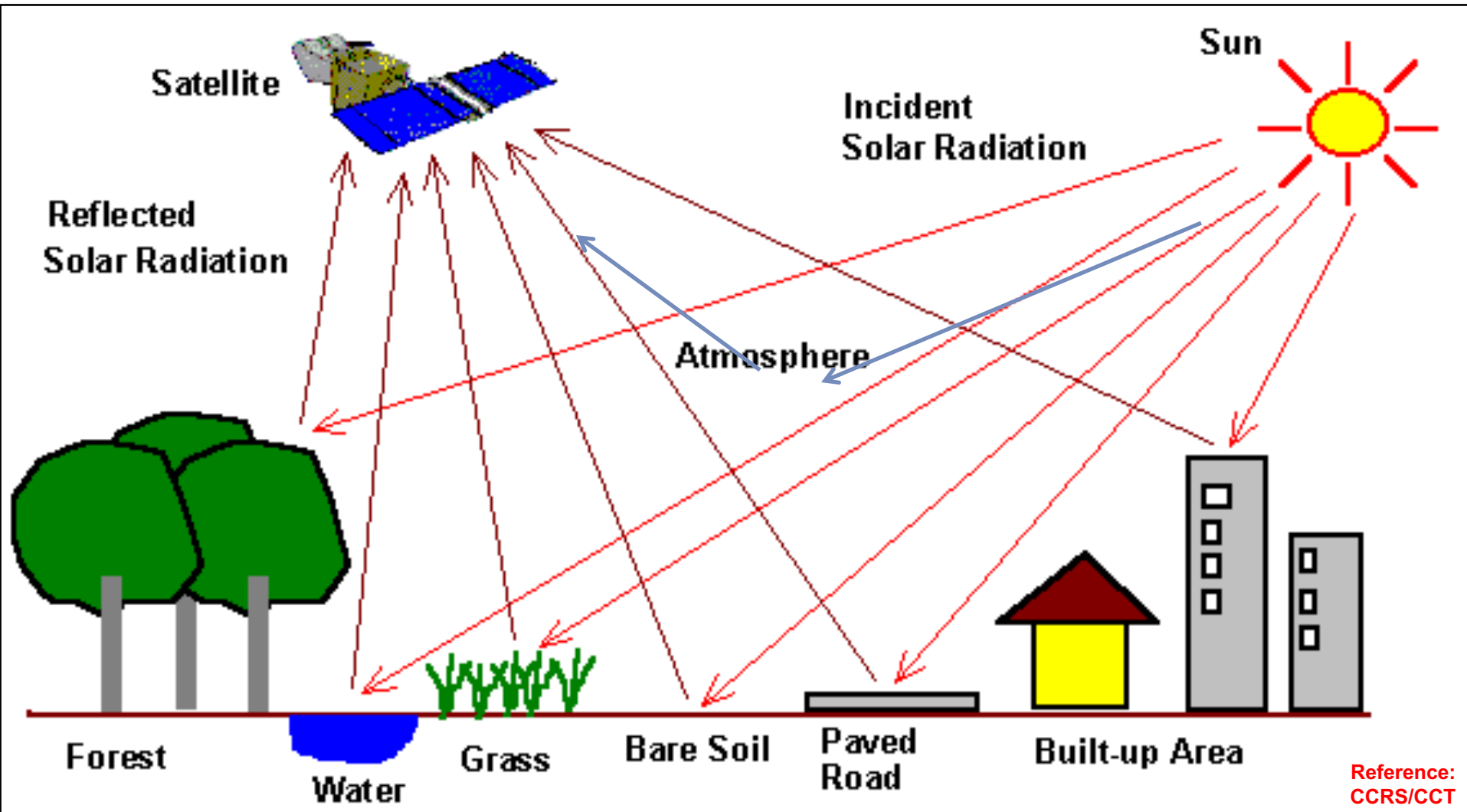
Measuring Properties of the Earth-Atmosphere System from Space

- The intensity of reflected and emitted radiation to space is influenced by the surface and atmospheric conditions

- Thus, satellite measurements contain information about the surface and atmospheric conditions
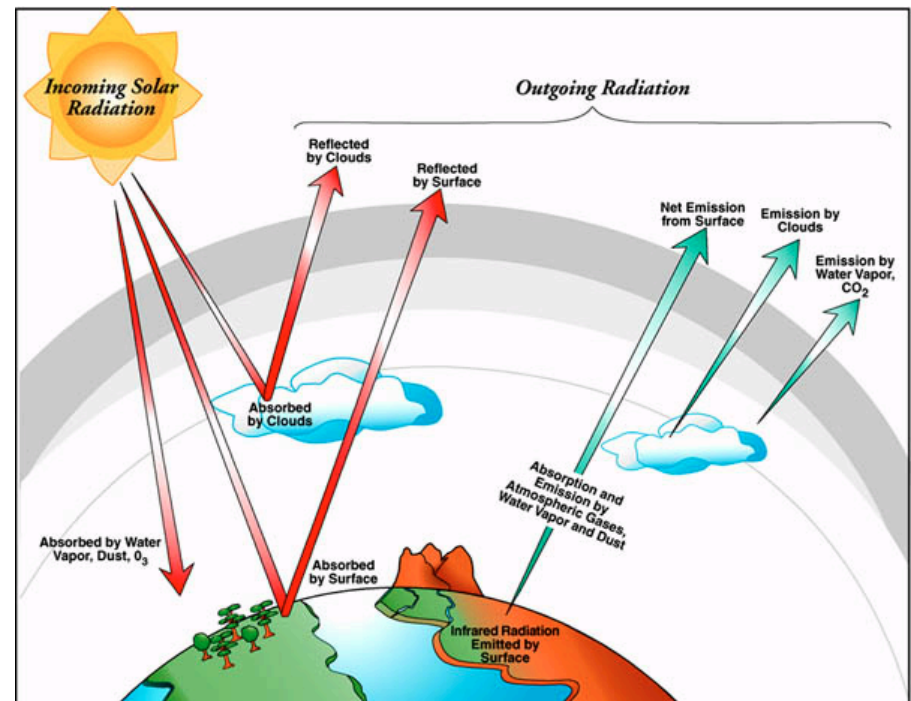
The Remote Sensing Process
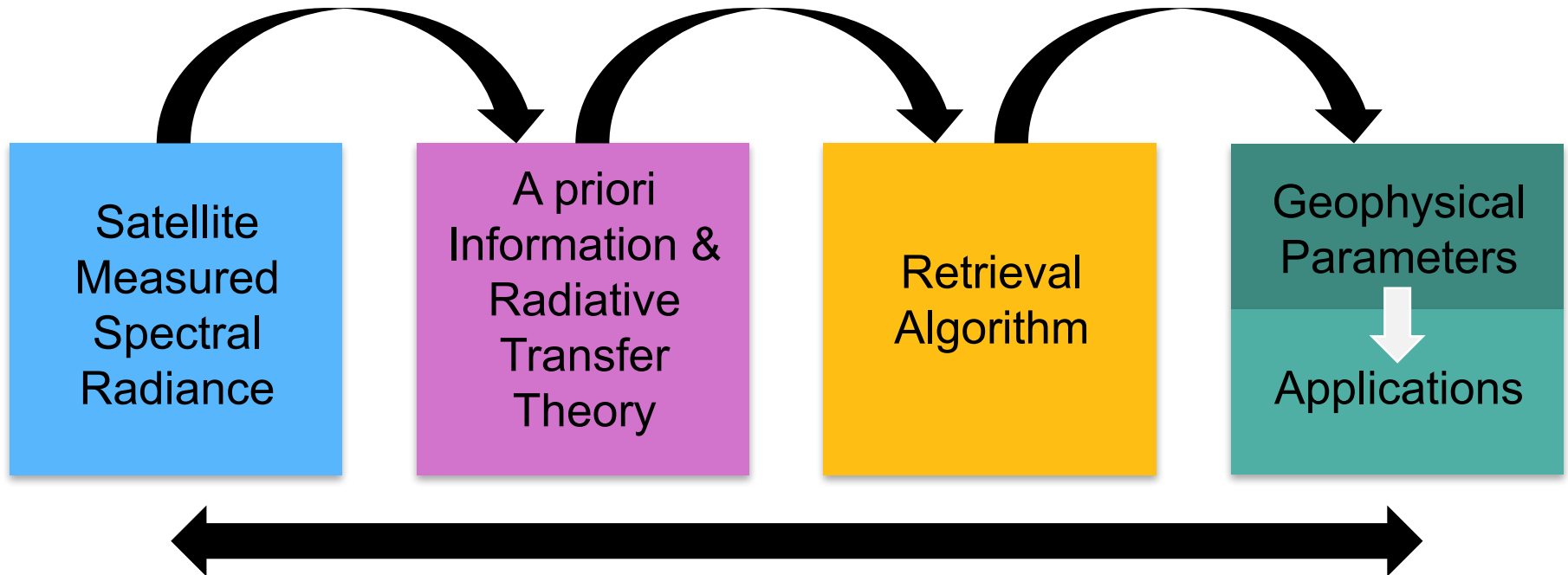
Characterizing Satellites and Sensors

- **Orbits**
  - Polar vs. Geostationary

- **Energy Source**
  - Passive vs. Active…

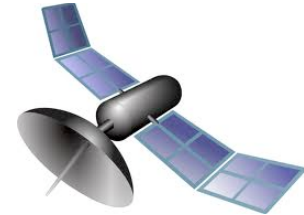- **Solar and Terrestrial Spectra**
  - Visible, UV, IR, Microwave...

- **Measurement Technique**
  - Scanning, non-scanning, imager, sounders...

- **Resolution (Spatial, Temporal, Spectral, Radiometric)**
  - Low vs. High

- **Applications**
  - Weather, Ocean Colors, Land Mapping, Atmospheric Physics, Atmospheric Chemistry, Air Quality, Radiation Budget, Water Cycle, Coastal Management...

Common Types of Orbits

Geostationary Orbit

© CCRS / CCT
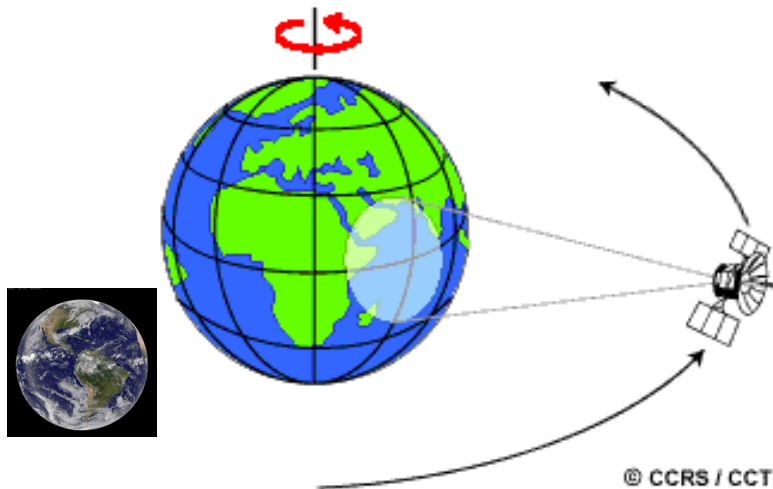
- Same rotational period as Earth
- Appears 'fixed' above Earth
- Over equator at ~36,000 km

Polar Orbit

© CCRS / CCT
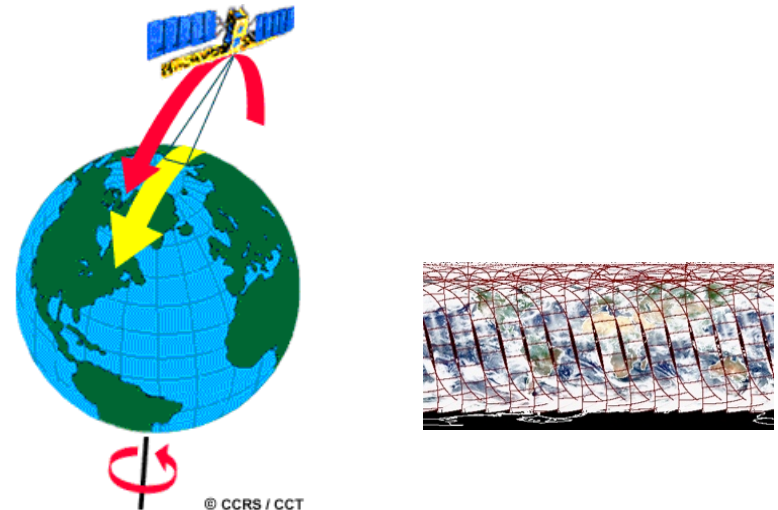
- Fixed, circular orbit above Earth
- ~600-1,000 km
- Sun-synchronous orbit with orbital pass at about the same **local solar time** each day

Observation Frequency

- Polar Orbiting Satellites:
  - 1-2 observations, per day, per sensor
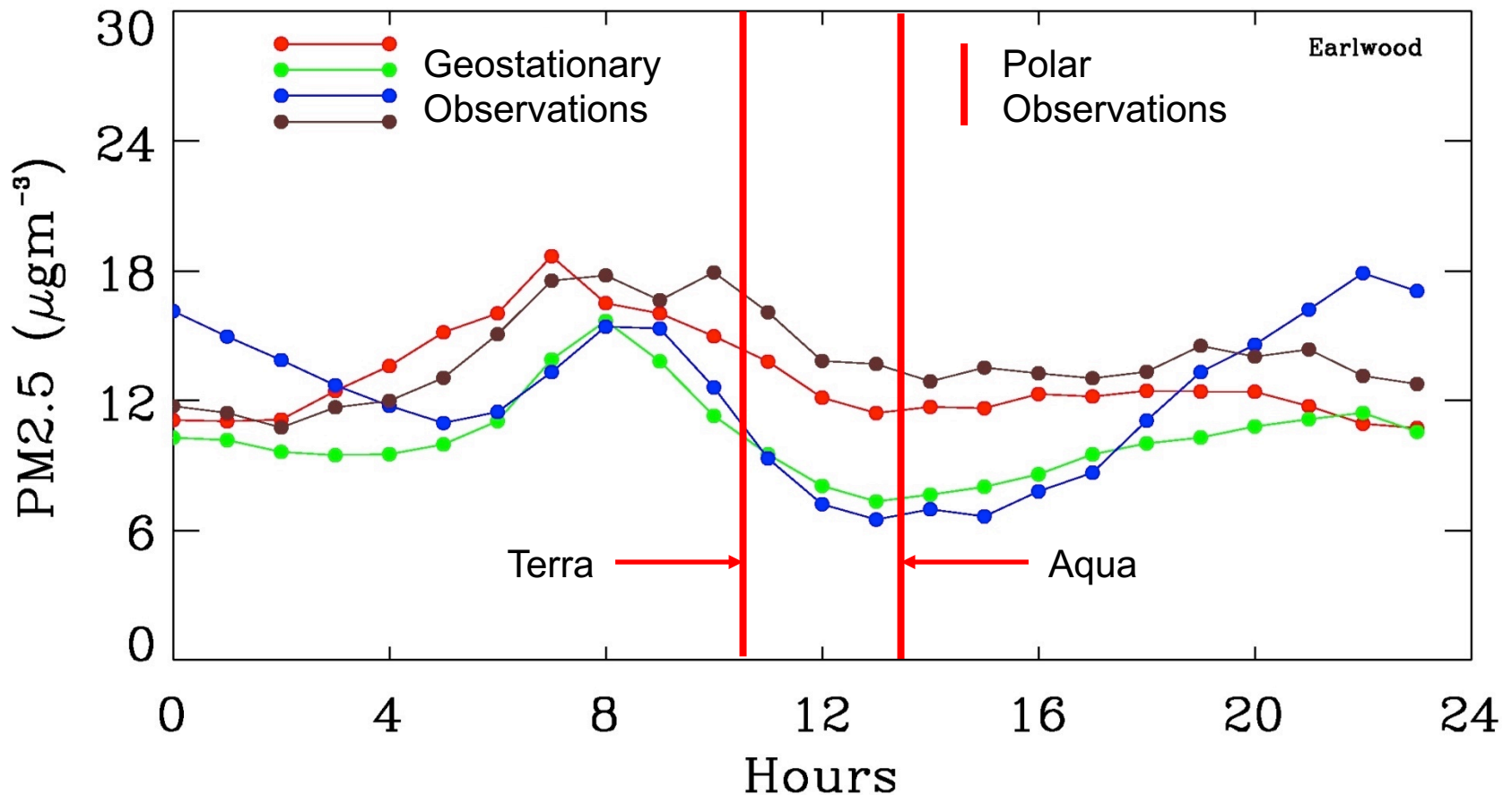
Satellite Coverage
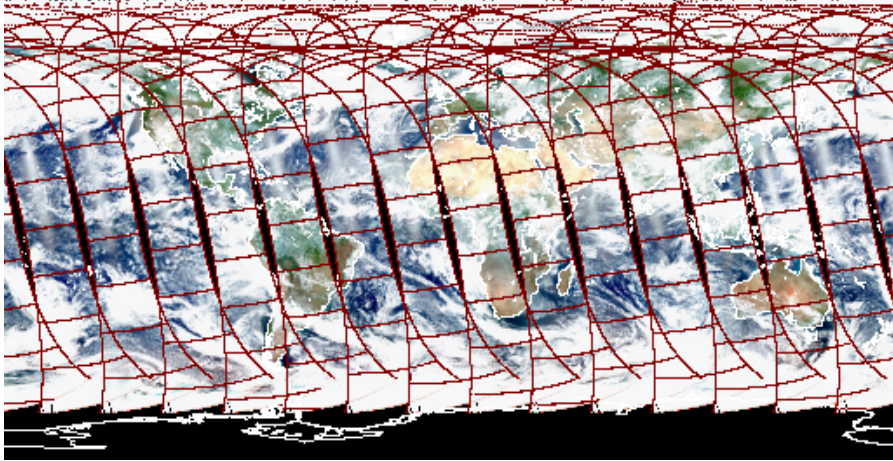
MODIS
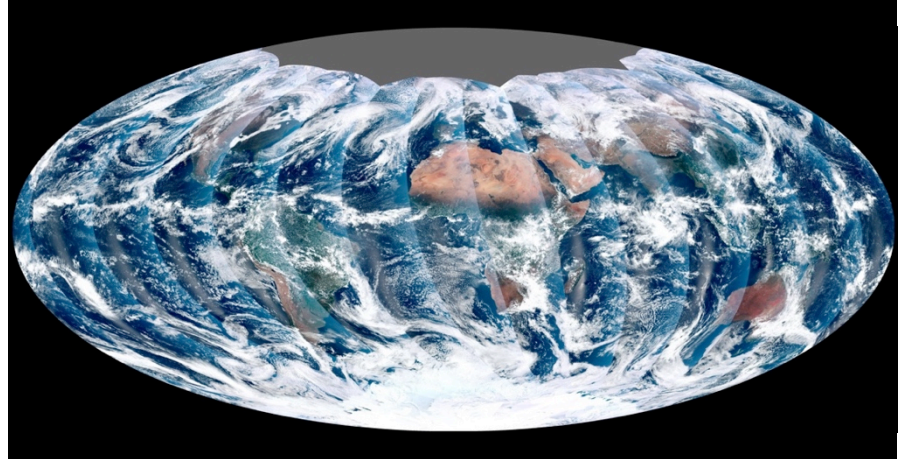
VIIRS
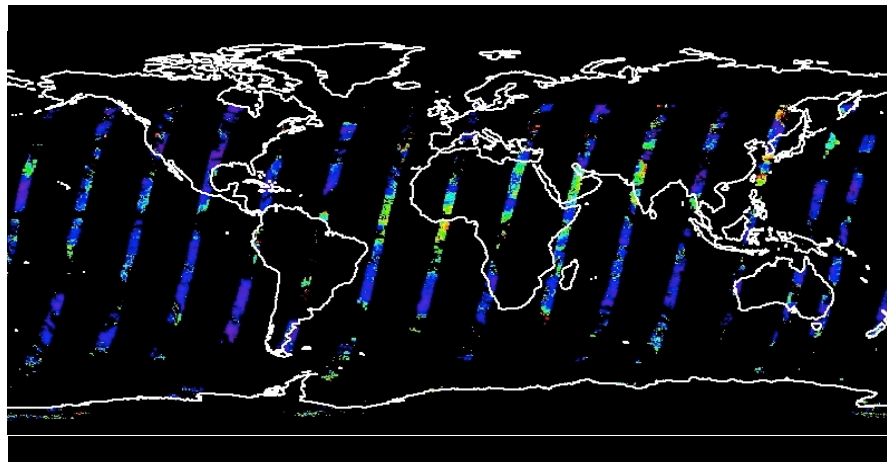
MISR

Active & Passive Sensors

Passive Sensors
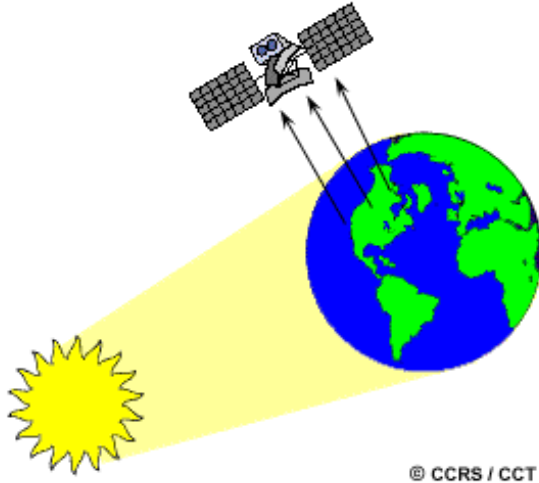
- Remote sensing systems that measure naturally available energy are called passive sensors

- MODIS, MISR, OMI, VIIRS

*Text Source: Natural Resources Canada

Active Sensors
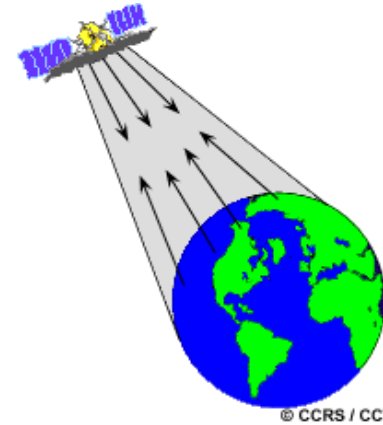
- The sensor emits radiation directed toward the target to be investigated. The radiation reflected from that target is detected and measured by the sensor.*

- CALIPSO

Remote Sensing – Types of Resolution

- Spatial Resolution
  - The smallest spatial measurement

- Temporal Resolution
  - Frequency of measurement

- Spectral Resolution
  - The number of independent channels

- Radiometric Resolution
  - The sensitivity of the detectors

Depends on the satellite orbit configuration and sensor design. Resolutions are different for different sensors.

Pixel – the Smallest Unit of an Image
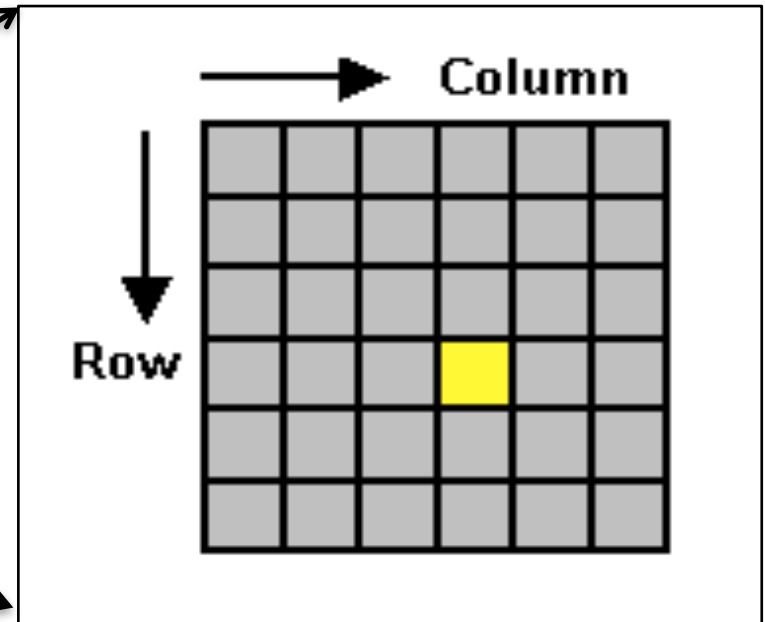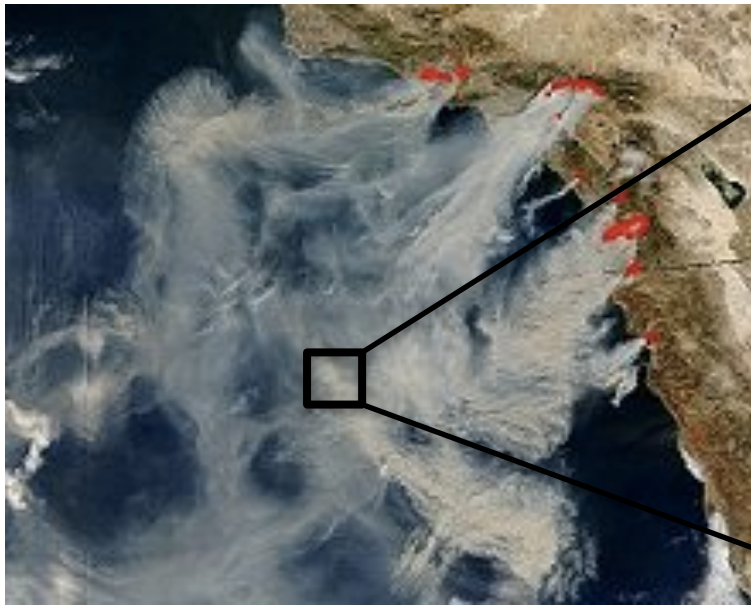
- A digital image is comprised of a two dimensional array of individual picture elements – called pixels – arranged in columns in rows
- Each pixel represents an area on the Earth's surface
- A pixel has an intensity value and a location address in the 2D image
- Spatial resolution is defined by the size of a pixel

*Text Source: Center for Remote Imaging, Sensing & Processing

Why is spatial resolution important?

- **MODIS**
  - 250 m – 1 km
- **MISR**
  - 275 m – 1.1 km
- **OMI**
  - 13x24 km
- **VIIRS**
  - 375 m
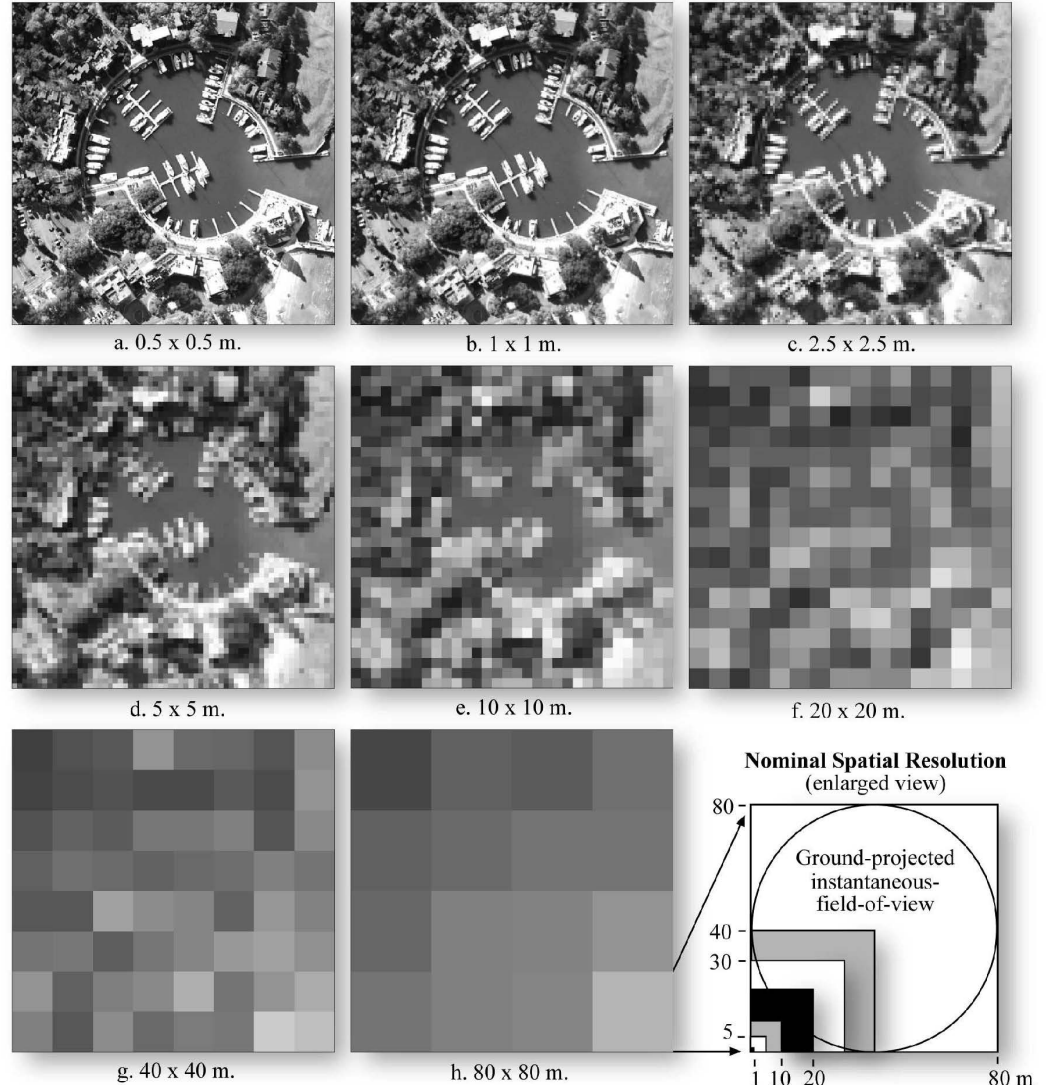
Source: Introductory Digital Image Processing,
3rd edition, Jensen, 2004

Imagery of Harbor Town in Hilton Head, SC, at Various Nominal Spatial Resolutions

a. 0.5 x 0.5 m. b. 1 x 1 m. c. 2.5 x 2.5 m.
d. 5 x 5 m. e. 10 x 10 m. f. 20 x 20 m.
g. 40 x 40 m. h. 80 x 80 m.

Nominal Spatial Resolution (enlarged view)

Ground-projected instantaneous-field-of-view

Spectral Resolution

- Spectral resolution describes a sensor's ability to define fine wavelength intervals

- The finer the spectral resolution, the narrower the wavelength range for a particular channel or band

- **Multispectral Sensors**
  - MODIS
  - Low spectral resolution

- **Hyperspectral Sensors**
  - OMI, AIRS
  - High spectral resolution

0.4 μm   0.7 μm

Black & White Film   Blue+Green+Red

0.4   0.5   0.6   0.7

Colour Film   Blue   Green   Red

© CCRS / CCT

Low spectral resolution

High spectral resolution
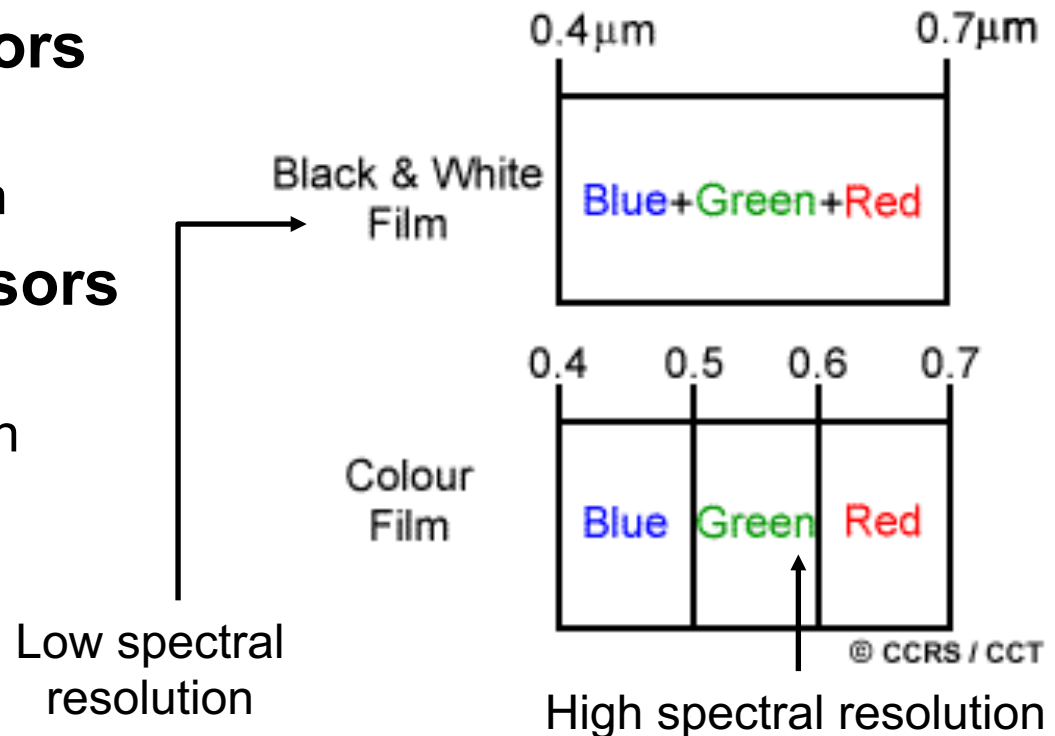
Why is spectral resolution important?
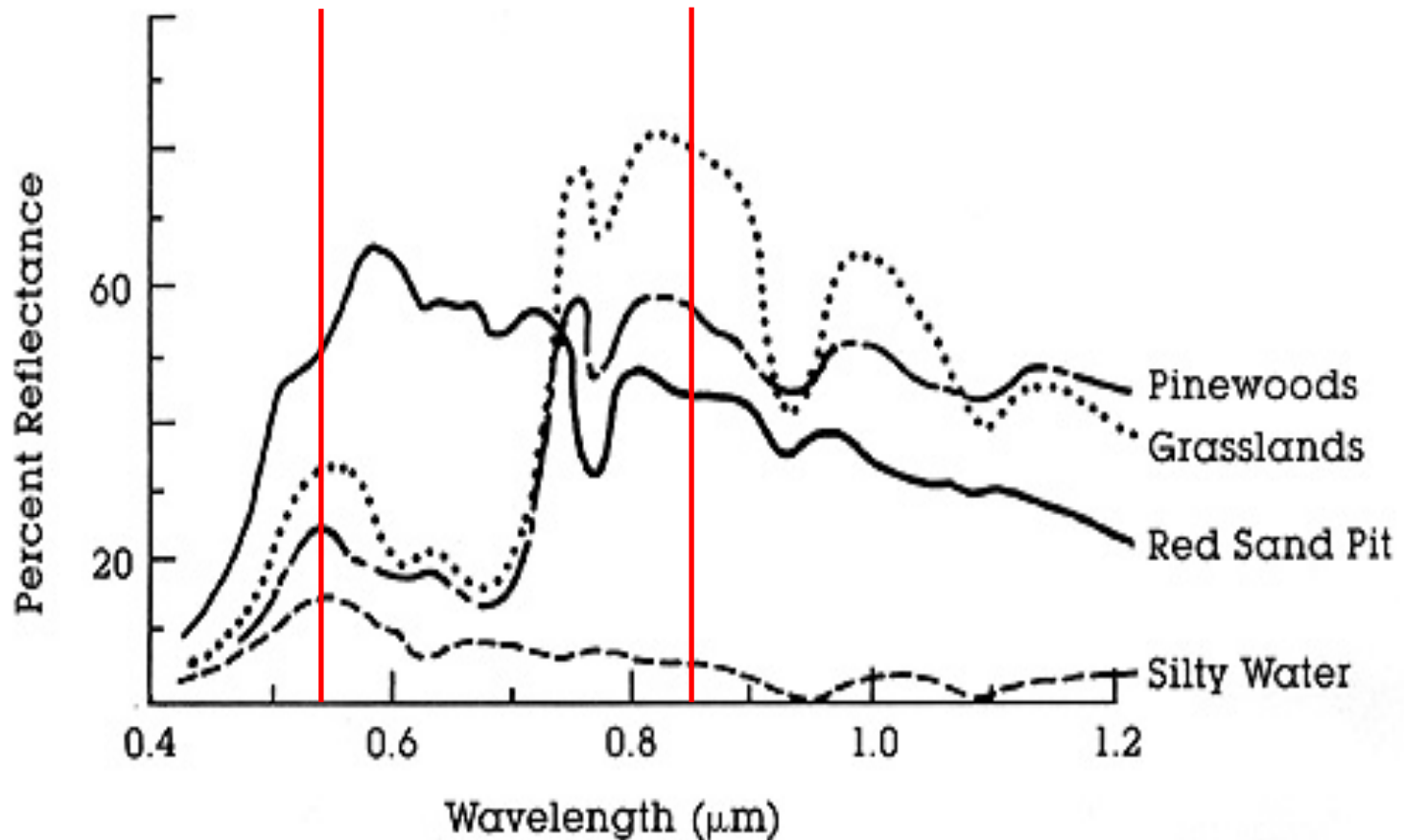
Radiometric Resolution

- Imagery data are represented by positive digital numbers that vary from 0 to (one less than) a selected power of 2
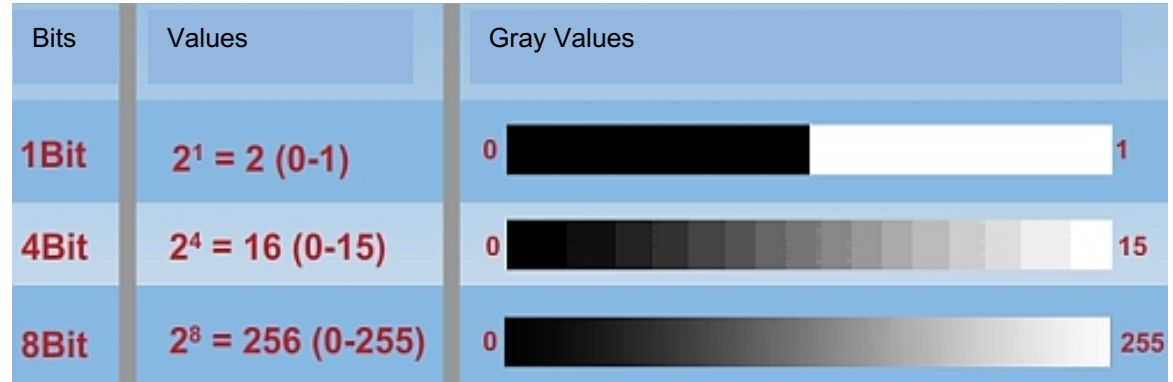- The maximum number of brightness levels available depends on the number of bits (**represents radiometric resolution**) used in representing the energy recorded
- The larger this number, the higher the radiometric resolution

- 12 bit sensor (MODIS, MISR)
  - 2^{12} or 4,096 levels
- 10 bit sensor (AVHRR)
  - 2^{10} or 1,024 levels
- 8 bit sensor (Landsat 7 TM)
  - 2^{8} or 256 levels
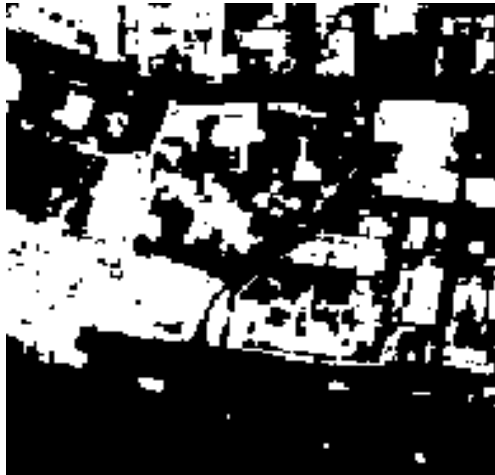
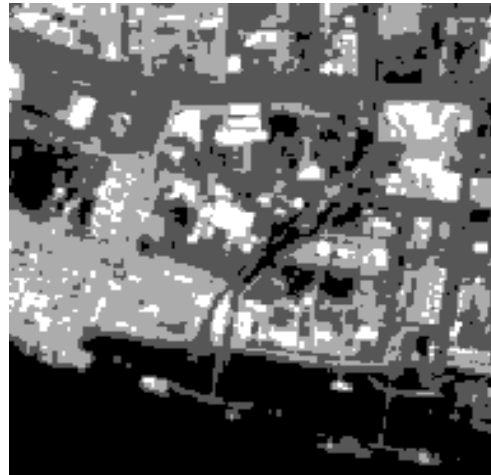| Bits	Values	Gray Values	
1Bit	$2^1 = 2$ (0-1)	0	1
4Bit	$2^4 = 16$ (0-15)	0	15
8Bit	$2^8 = 256$ (0-255)	0	255

Source: FIS

*Text Source: Natural Resources Canada

Radiometric Resolution

2 - levels

4 - levels

8 - levels

16 - levels

**(MODIS
4096 levels)**

In classifying a scene, different classes are more precisely identified if radiometric resolution is high.

Temporal Resolution

- How frequently a satellite can provide observations of the same area on the Earth

- It mostly depends on the swath width of the satellite – the larger the swath, the higher the temporal resolution
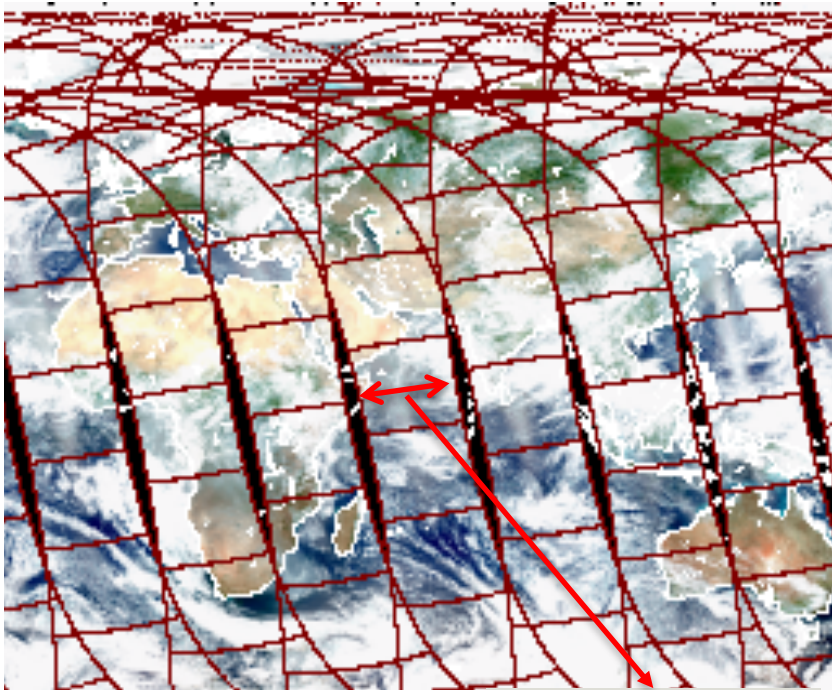
swath width

- MODIS
  – 1-2 days
- OMI
  – 1-2 days
- MISR
  – 6-8 days
- VIIRS
  – 1 day
- Geostationary
  – 10 min – 1 hr

Remote Sensing Tradeoff

It is very difficult to obtain extremely high spectral, spatial, temporal, **AND** radiometric resolutions all at the same time

Future Satellite Capabilities for Air Quality Applications

GOES-R

- Expected Launch: November, 2016
- Advance Baseline Imager (ABI): 16 Spectral Bands
- Very High Temporal Resolution: 15 min – 30 seconds

GOES-R

	ABI	Current GOES Imager
Spectral Coverage	16 bands	5 bands
Spatial Resolution		
0.64 μm Visible	0.5 km	~ 1 km
Other visible/near-IR	1.0 km	n/a
Bands (>2 μm)	2 km	~ 4 km
Spatial Coverage		
Full Disk	4 per hour	Scheduled (3 hrly)
CONUS	12 per hour	~4 per hour
Mesoscale	Every 30 sec	n/a
Visible (reflective bands)		
On-orbit calibration	Yes	No

GOES-R
Advanced Baseline Imager (ABI)

New capabilities.
Higher resolution.
Faster coverage.

GOES R

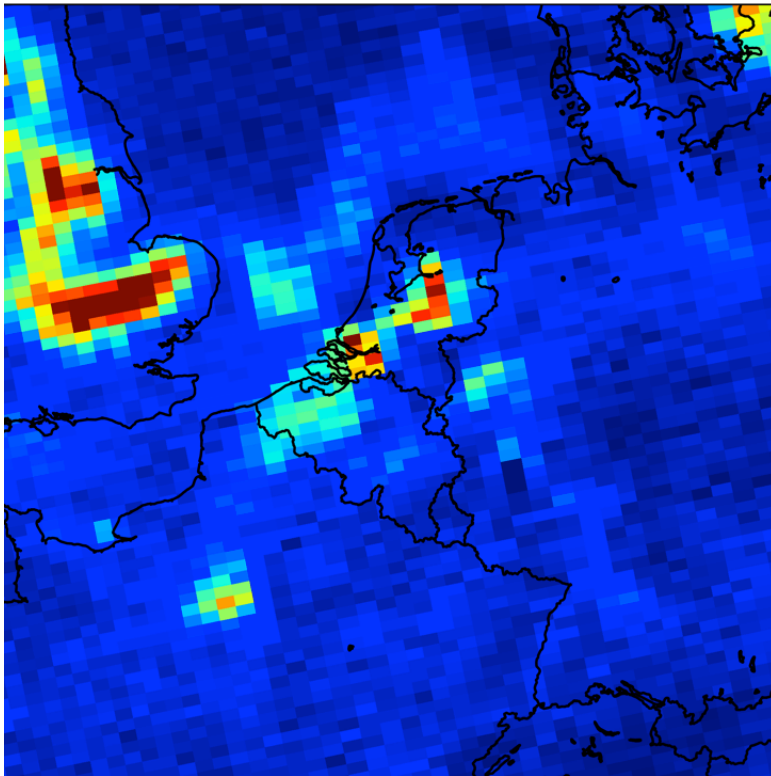# *European Space Agency* TROPOMI

TROPOMI Highlights
- **Launch 2016**
- **Observes whole globe**
- **Sub-urban spatial resolution (7 km x 7 km)**
- ***1x/day:* NO$_2$, ozone (0-2 km vertical), aerosol, clouds, formaldehyde, glyoxal, SO$_2$, CO, methane**
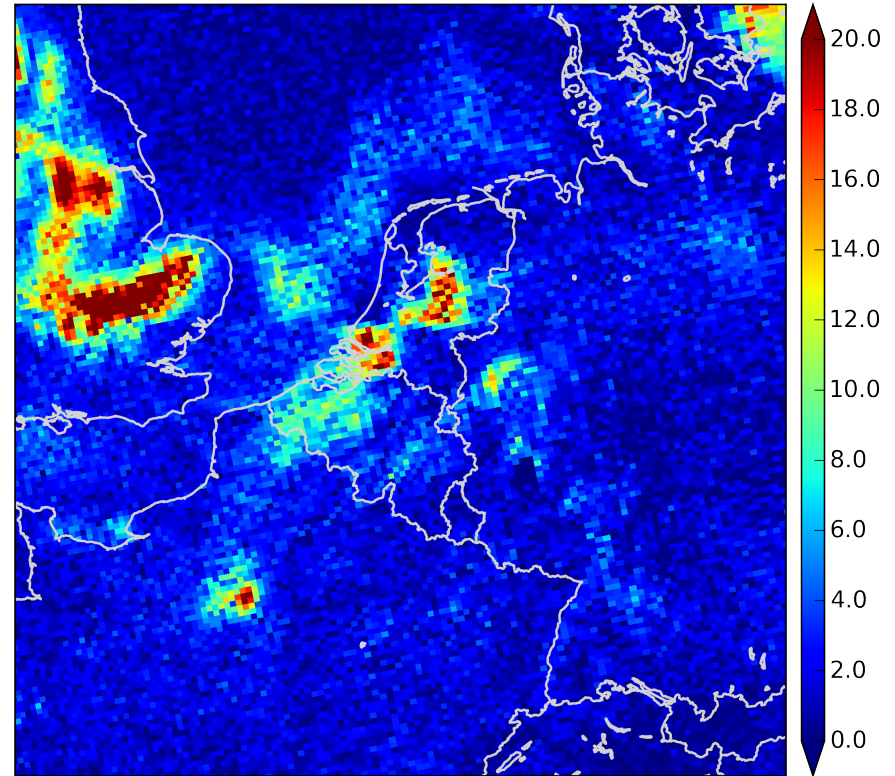
Measuring on Sub-Urban Level

GOME-2 (NO2)

SCIAMACHY (CO)
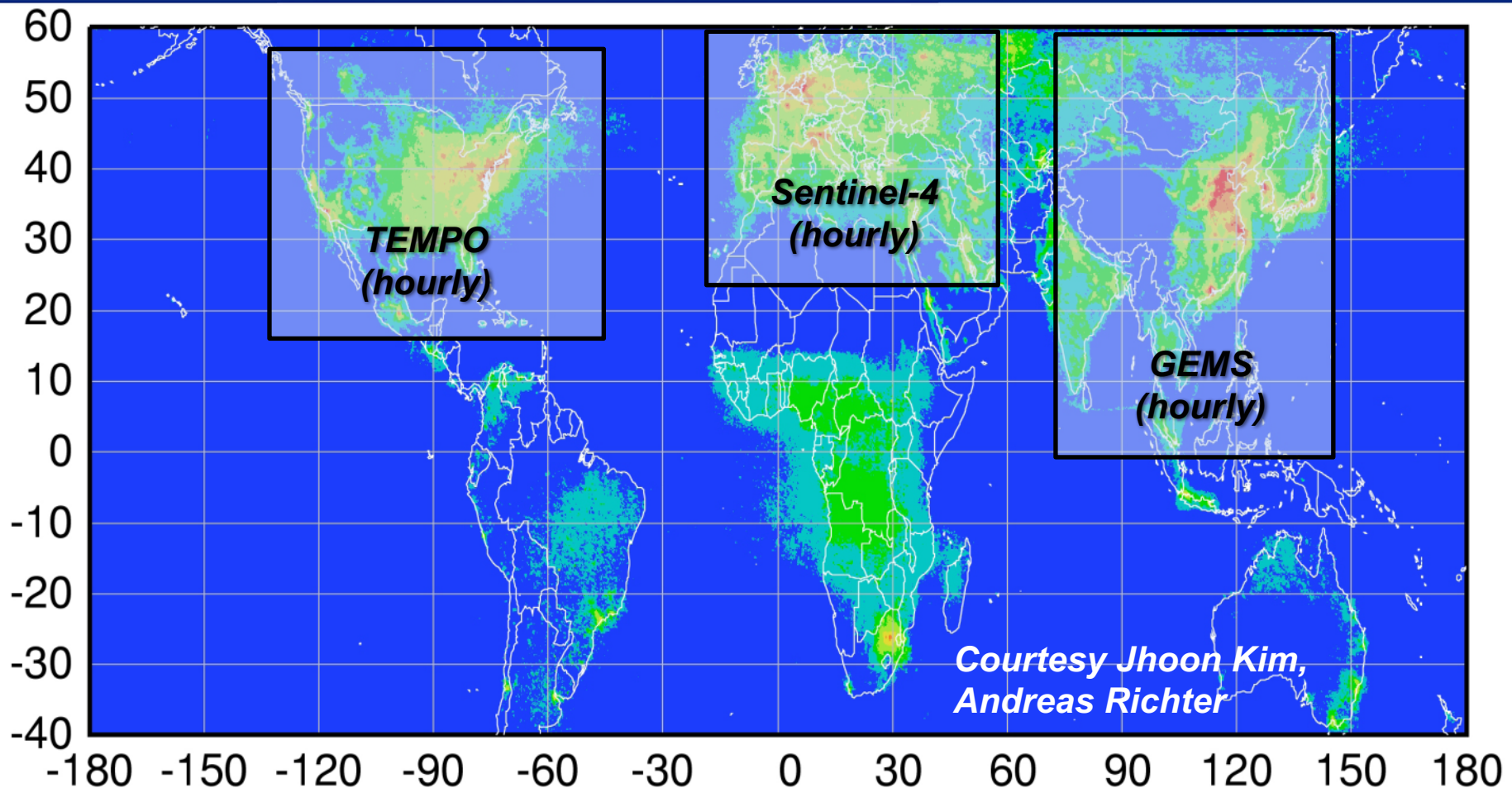
The Hague

Utrecht

OMI

13x24 km^2

7x7 km^2

TROPOMI

Rotterdam

SCIAMACHY (NO2)

Slide courtesy: Bryan Duncan
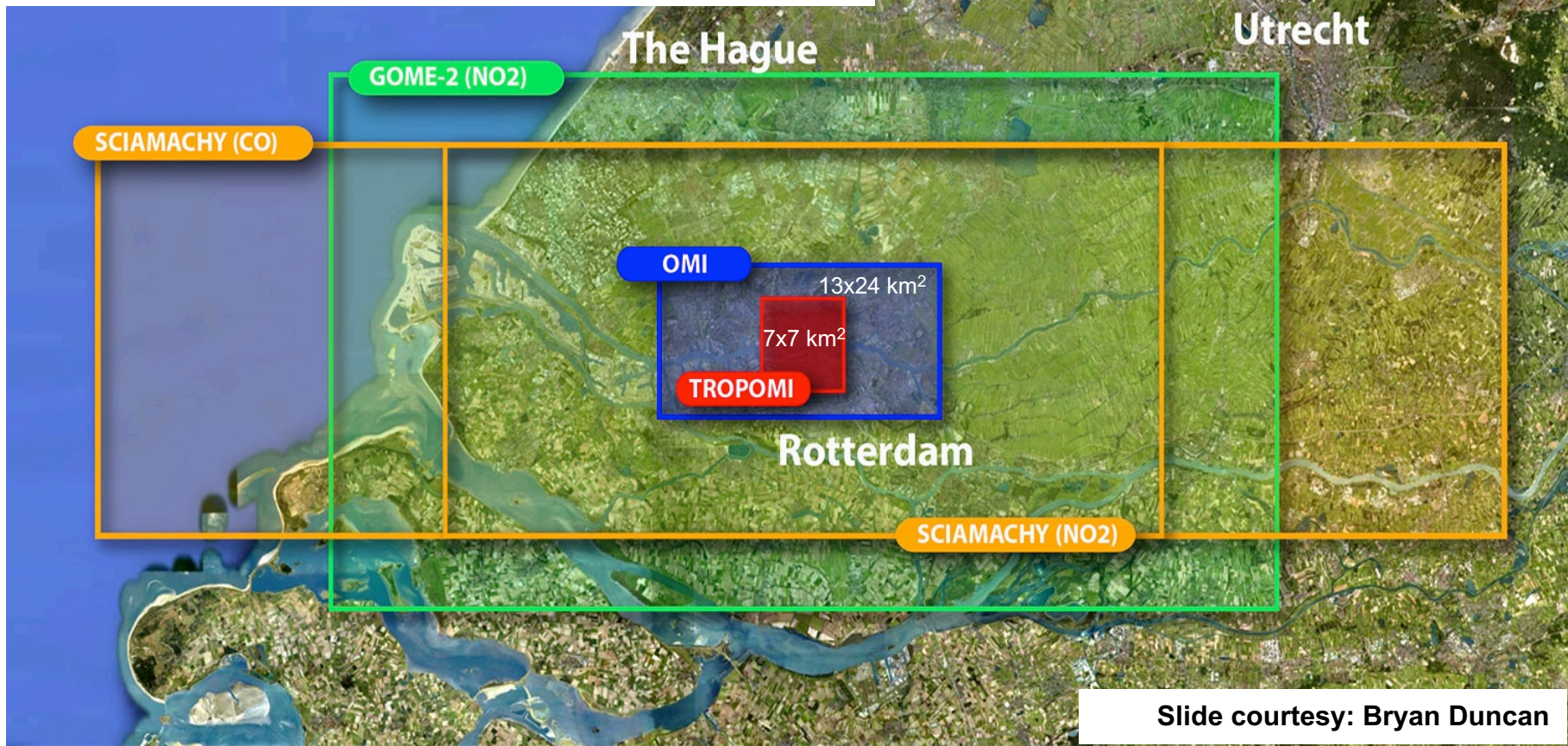
TROPOMI: Impact of Resolution

**OMI (now)**

TROMPOMI (launch 2016)

Policy-relevant science and environmental services enabled by common observations

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support United Nations Convention on Long Range Transboundary Air Pollution
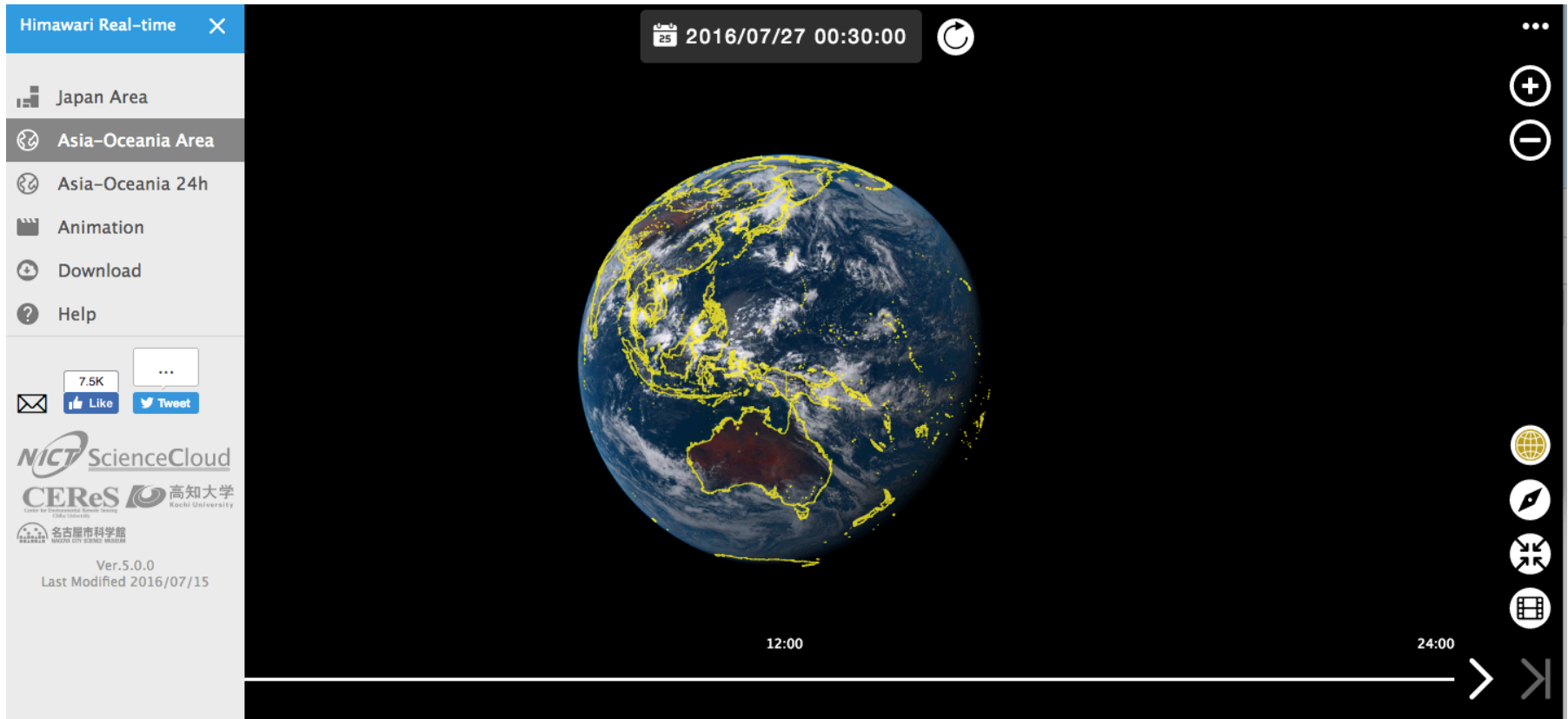
Slide from KChance

TEMPO

- Geostationary over North America

- High Temporal Resolution
  - 1 hr

- High Spatial Resolution
  - 2.2 x 4.7 km

- Spectral Range
  - 290-740nm

- Data Products:
  - O_3, NO_2, SO_2, H_2CO, $C_2H_2O_2$, aerosols, cloud parameters, & UVB radiation

- Expected Launch: 2020

Himarawi 8

http://himarawi8.nict.go.jp/
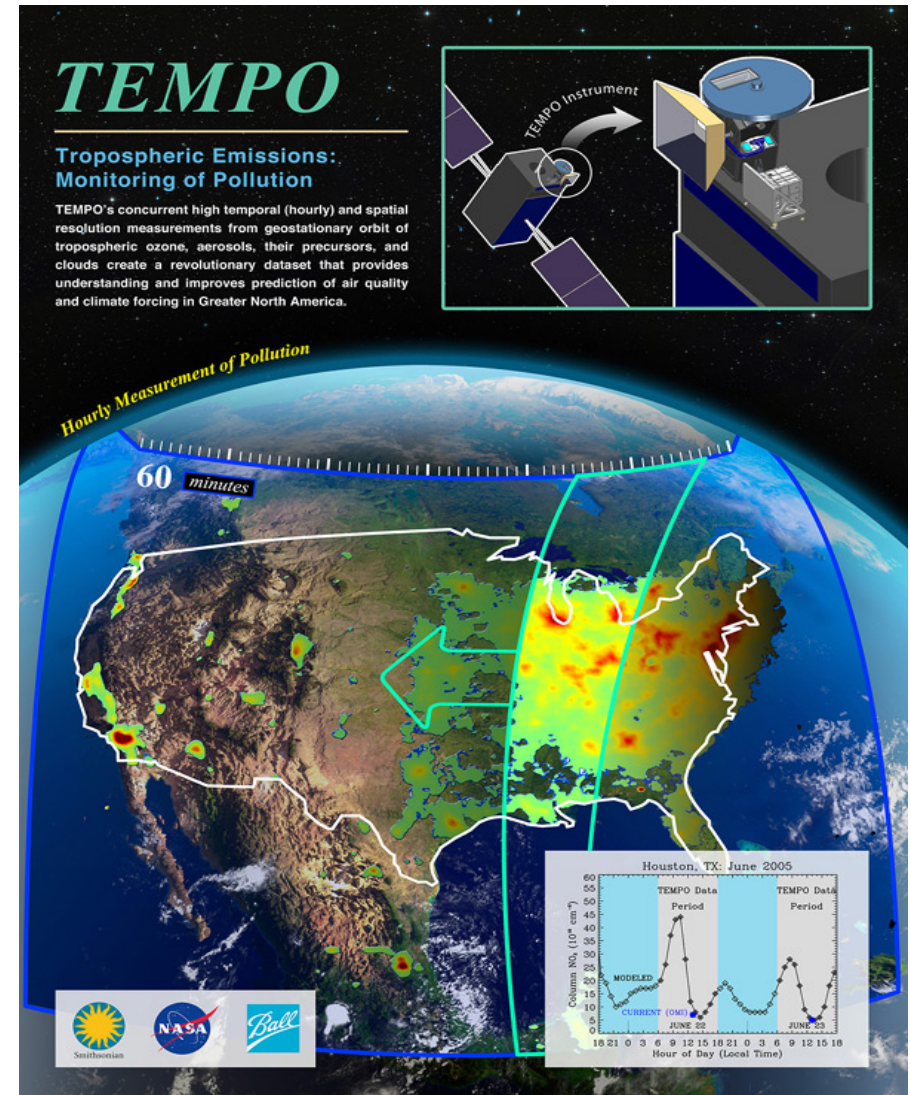
- Japan Meteorological Agency
- Launch date: October 7, 2014

Questions & Discussion

- Can satellites help fill some of the data gaps?

- What are advantages of polar orbiting satellites as compared to geostationary satellites?

- What are the tradeoffs of remote sensing?

- What are the sources of uncertainties in satellite observations for air quality applications?

Questions?